Norimasa Nakamura
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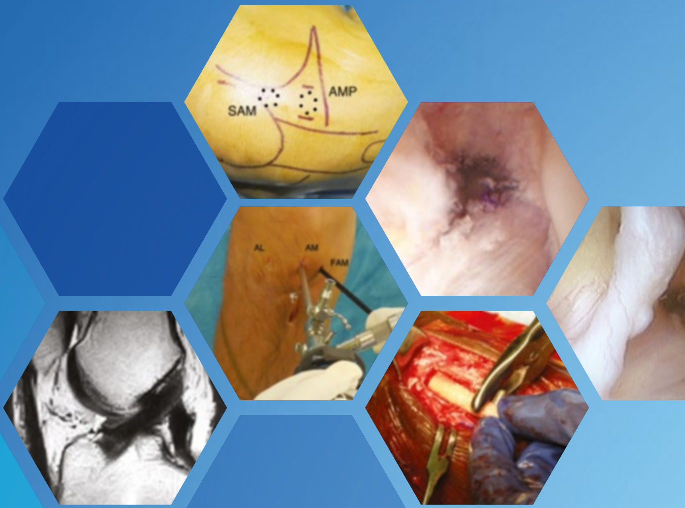

Controversies in the Technical Aspects of ACL Reconstruction

An Evidence-Based Medicine Approach

International Society of Arthroscopy, Knee Surgery & Orthopaedic Sports Medicine · 1995

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Preface

Anterior cruciate ligament (ACL) surgery has changed and evolved extensively for over the last few decades. There are many controversies that exist with respect to the technical aspects of this surgery. In this book, we attempted to present the controversial aspects in an evidence-based fashion. In several cases, the topic is so controversial that we presented chapters presenting the evidence for either side of the argument. Evidence-based medicine is when the physician uses the best available literature to assist in decision-making for a given patient. While there is not always a perfect answer for a given clinical dilemma, we attempted to present the information in as unbiased manner as possible. The following pages will take the reader through ACL injury from prevention to clinical decision-making to surgical technique. We hope that we assist the reader to take better care of their patients using the available evidence summarized by authors from around the globe representing ISAKOS.

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ACL Prevention Programs

1

Joseph N. Liu, Michael D. Hendel,
Grethe Myklebust, and Robert G. Marx

1.1 Introduction

Anterior cruciate ligament (ACL) injuries are a common knee injury, with approximately 100,000–200,000 occurring each year in the United States alone [25]. Female athletes have a four to six times higher incidence of noncontact injuries, with an estimated rate of one in 60–100 female high school athletes suffering ACL injuries [6, 25]. While a great deal of research has been performed on the surgical techniques and rehabilitation following ACL reconstruction, only recently has there been an emphasis on prevention, with a large body of research over the last 15 years demonstrating that prevention programs can effectively decrease the number of ACL tears ([8, 11, 17, 21–23, 27, 31]; Soligard 2008). Additionally, these prevention programs have been shown to reduce other knee injuries, ankle injuries, and overuse injuries [15]. The purpose of this chapter is to review modifiable causes for ACL injuries and the current literature regarding prevention programs that target risk factors that predispose patients to ACL injuries.

1.2 Mechanism of Injury and Modifiable Risk Factors

Approximately 70 % of all ACL injuries occur by noncontact mechanisms [1, 19]. Recent literature has demonstrated that the highest ACL loads occur with the knee loaded in valgus, internal rotation, and concomitant quadriceps contraction with insufficient hamstring strength (Shimokochi 2008; [14, 29, 39]). This combination typically occurs in movements associated with declaration, cutting maneuvers, or jump landings [1]. While many intrinsic risk factors such as gender, anatomical differences, and hormonal changes predispose athletes to ACL tears, addressing modifiable neuromuscular imbalances has demonstrated promising results ([8, 11, 17, 21, 22, 27]; Soligard 2008). These neuromuscular imbalances include ligament dominance, quadriceps dominance, leg dominance, and trunk dominance; the mechanism in which these imbalances lead to increased loads on the ACL is reviewed in the following sections.

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1.2.1 Ligament Dominance

Ligament dominance refers to an imbalance between neuromuscular and ligamental control of knee stability, resulting in the knee ligamentous system absorbing ground reaction forces instead of the lower extremity musculature. The lack of control demonstrated by ligament dominance leads to increased valgus motion and high torque at the knee and ACL and is best seen in the front plane with landing and cutting movements such as single-leg landing, pivoting, and deceleration movements. Poor trunk control can also lead to increased valgus stress at the knee; the ground reaction forces that follow trunk motion tend to shift the center of mass laterally to the center of the knee resulting in a dynamic valgus positioning.

1.2.2 Quadriceps Dominance

Quadriceps dominance refers to the preferential activation of the quadriceps compared to the hamstrings and occurs during maneuvers such as cutting and jumping [10, 12]. With the knee flexed less than 30°, increased quadriceps activation without co-contraction of the hamstring and gastrocnemius results in increased strain on the ACL [40]. The hamstring provides a stabilizing force on the knee, pulling the tibia posteriorly to decrease ACL stress by resisting anterior and lateral tibial translation and rotation. Unlike females, males tend to activate their hamstrings first when landing, which may partially explain their lower risk of ACL injuries. Additionally, studies have shown that females have a lower hamstring-to-quadriceps ratio, sustain quadriceps activation longer during cutting movements [3], and preferentially activate their quads during jump landings resulting in stiff-legged landings, which prevent the dissipation of ground reaction forces [4]. All of these neuromuscular deficiencies related to quadriceps dominance demonstrate the importance of addressing hamstring strength in prevention programs.

1.2.3 Leg Dominance

Leg dominance refers to neuromuscular asymmetry from side to side that may place both limbs at risk [12]. Deficits in strength, flexibility, and coordination may compromise the weaker limb's ability to dissipate forces while placing excessive stress on the stronger limb. Single-leg exercises, such as single-limb stance or hops, and assessing difference in performance can be used to identify leg dominance. The treatment of leg dominance involves progression of quality double-leg movements to single-leg movements and focuses on ensuring that each limb works independently.

1.2.4 Trunk Dominance

Trunk dominance relates to the inability of an athlete to control his or her center of gravity during athletic movements, usually due to a decrease in core strength or neuromuscular control [3, 9, 16, 26]. This type of imbalance occurs more often in women than in men, likely related to a female's center of mass located higher from the ground due to the distribution of body mass and body fat in women. With trunk imbalance and a lack of core strength, excessive trunk motion is seen in the frontal plane, resulting in altered knee stability and increased injury risk [9, 13, 16, 26]; Bien 2011).

1.3 Anterior Cruciate Ligament Prevention Programs

Most ACL prevention programs combine a variety of strategies aimed at modifying the risk factors described above. These programs use a multifaceted approach and include components of proprioception training, plyometric training, neuromuscular training, and strengthening (Hewett et al. 2002; [16]). Neuromuscular training is designed to prevent injury by enhancing joint stability, position sense, and joint reflexes [24]. The literature stresses the importance of reducing the valgus moment at landing to reduce risk of ACL injury [28, 30]. Proprioception, defined as the awareness of the orientation and positioning of one's body, can be trained to improve an athlete's coordination, positioning, and balance in multiple planes in the presence or absence of outside variables [2]. Plyometrics includes jumping, landing, and cutting maneuvers while avoiding knee valgus, at varying intensities. Multiple studies have demonstrated the benefits of a multifaceted approach to ACL prevention which includes neuromuscular training, plyometrics, agility, and strengthening [5, 8, 11, 13, 17, 22, 27]; the addition of these training programs into an athlete's warm-up has also been effective [1, 5, 10, 12, 13, 24, 31]. The details of several well-known programs and their outcomes are discussed in the following sections.

1.3.1 Proprioceptive Training

In 1996, Caraffa et al. reported the results of a proprioceptive training program and its ability to reduce the risk of ACL injury. In a study involving semiprofessional and amateur Italian soccer players, two groups of 300 athletes were compared; the first group was instructed to train 20 min per day in five different phases of increasing balance difficulty: no balance board, rectangular balance board, round board, combined round and rectangular board, and the so-called BABS board. The control group trained normally without any special balance training. The results were extremely effective: only 10/300 (3.33 %) players in the intervention group sustained an ACL injury compared to 70/300 (23.3 %) in the control group ($p < 0.001$).

The success of Caraffa's program, however, has not been replicated by more recent studies. In 2000, [32] reported that there were no differences in the rate of ACL injuries between 221 Swedish female soccer players randomized to a balance board regimen (121) or regular training (100). Surprisingly, the intervention group had more ACL injuries than the control group, albeit not statistically significant. They concluded that while balance and proprioceptive training may be useful to include in an ACL prevention program, on their own they may be insufficient. Neuromuscular and biomechanical deficiencies must also be addressed.

1.3.2 Neuromuscular Training Programs

1.3.2.1 Sportsmetrics Anterior Cruciate Ligament Injury Prevention Program

The *Sportsmetrics Anterior Cruciate Ligament Injury Prevention Program* (Dr. Frank Noyes, Cincinnati Sports Medicine, Cincinnati, OH) was first published in a prospective, nonrandomized study by Hewett et al. in 1999. This study, which consisted of three groups, followed 1,263 high school soccer, volleyball, and basketball athletes for 1 year. Group 1 (366 girls) underwent a neuromuscular training program designed to improve flexibility and muscular strength. This training program included dynamic warm-ups, plyometrics and strength training, and flexibility exercises and was recommended for 60–90 min per session, three times per week for six weeks. Group 2 (463 girls) were involved in competitive sports but did not participate in the training program. Group 3 (434 boys) acted as a control and did not have training. The untrained female group (Group 2) had a 3.6 higher incidence of injuries compared to the trained group (Group 1). There was, however, no difference in the incidence of injuries between the untrained boys (Group 3) and the trained girls (Group 1). As a follow-up, the *Sportsmetrics Warm-Up for Injury Prevention and Performance* program was created as a faster alternative, designed to be completed in 24 min by shortening the four components of the original program [7].

1.3.2.2 Myklebust's Anterior Cruciate Ligament Injury Prevention Program

In 2003, Myklebust et al. reported the results of a nonrandomized prospective intervention study of 1,705 female Norwegian handball athletes. Based on the exercises used by Caraffa et al. [2], the program consisted of three sets of exercises: running and cutting, wobble board, and mat balance exercises over fifteen minutes performed three times per week for 5–7 weeks (see Figs. 1.1, 1.2, 1.3, 1.4, and 1.5) [18]. These exercises were designed to improve knee control and awareness during athletic maneuvers including cutting, jumping, and landing. Over the course of three seasons, there was a trend ($p=0.06$) toward reduction of ACL injury incidence in the intervention group for the athletes participating in the elite division compared to the control group. However, athletes in the other groups demonstrated no statistical decrease in rates of ACL injury compared to control ($p=0.15$).

1.3.2.3 Prevent Injury and Enhance Performance Program

The five phases of the Prevent Injury and Enhance Performance (PEP) program were devised by the Santa Monica Sports Medicine Research Foundation [17]. These include dynamic warm-up, strengthening, plyometrics, agility training, and lower extremity stretching, with all exercises designed to be completed in 15–20 min. The results of the PEP program were first reported by Mandelbaum et al. [17] in a prospective nonrandomized study. A total of 1,885 female soccer players aged 14–18 participated in the program over two seasons. A 88 % decrease and 74 % decrease in ACL injuries was observed in the first and second seasons, respectively, in the intervention group. In 2008, Gilchrist et al. [5] reported the results of the PEP program in a randomized controlled trial involving female collegiate soccer players. The study included 583 athletes in the PEP intervention group compared to 852 in the control group and found a 3.3 times higher rate of noncontact ACL injury in the control group.

Fig. 1.1 Level 4: throwing ball with partner on wobble board—*correct* knee position on wobble board. Throw a ball back and forth with a partner while each of you stands on one leg on a wobble board (Figures were reprinted with permission from *The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury* published by Demos Health, 2012)

1.3.2.4 Knee Injury Prevention Program

In 2011, LaBella et al. presented the results of a cluster randomized controlled trial using the Knee Injury Prevention Program (KIPP), a proprietary 20-min neuromuscular warm-up designed to reduce ACL injuries. A total of 90 coaches, 110 teams, and 1,492 high school female athletes from Chicago public schools participated. Coaches were clustered by school and then randomized to either the intervention group or the control group. Control coaches were asked to continue their normal routines, while intervention coaches underwent a 2-h training session to learn how to implement the

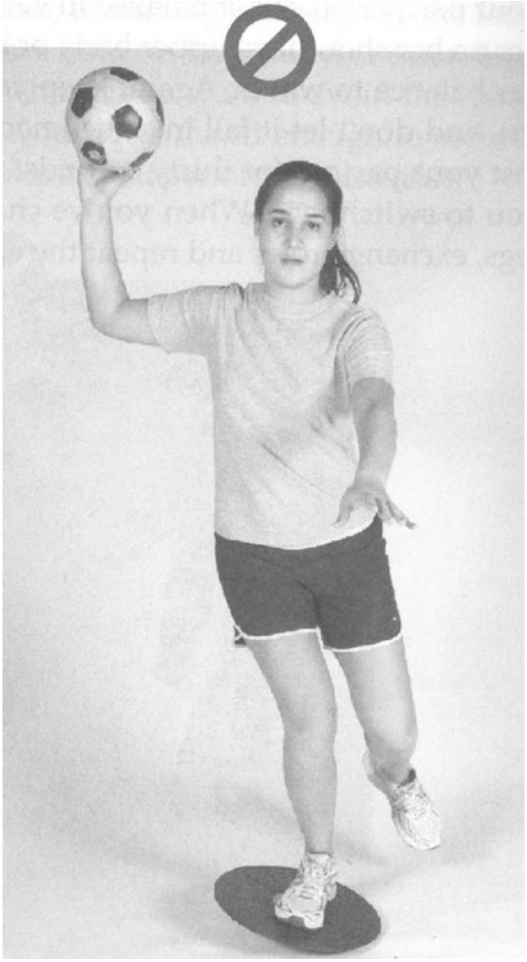


Fig. 1.2 Level 4: throwing ball with partner on wobble board—*incorrect* knock-kneed stance with pelvis dropped to one side (Figures were reprinted with permission from *The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury* published by Demos Health, 2012)

20-min neuromuscular warm-up, which included plyometrics, balance, progressive strengthening, and agility movements. Eighty percent of intervention coaches complied with the warm-up regimen. At the end of the season, there was a 56 % reduction in total noncontact lower extremity injuries in the intervention group compared with the control group (injury rate of 0.48 vs 0.10, $P = 0.04$). The intervention group also had lower rates of ankle sprains, knee sprains, and other lower extremity injuries.

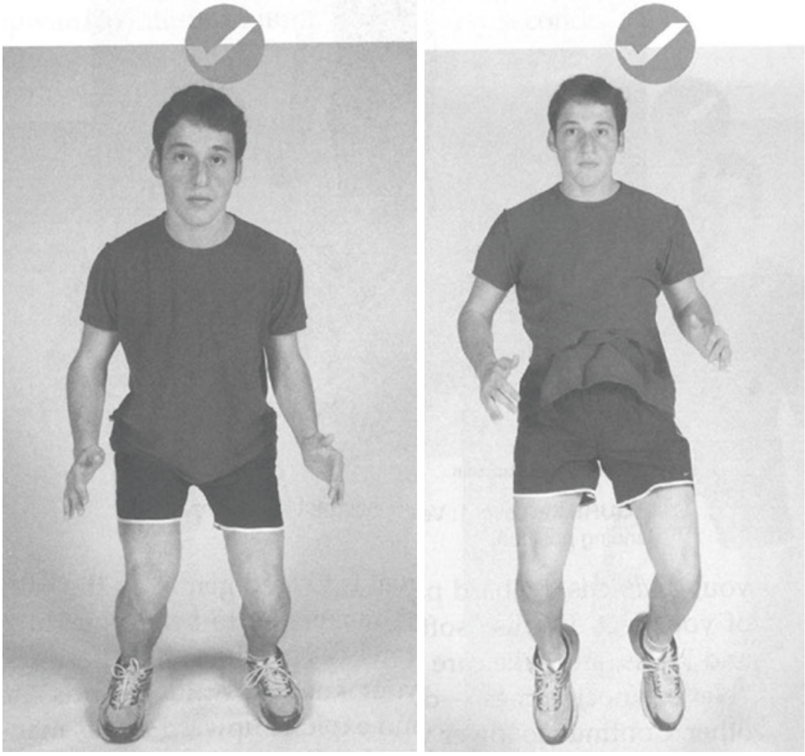
1.3.2.5 Knee Ligament Injury Prevention Program

In 2004, Irmischer et al. presented the results of a plyometric-based knee ligament injury prevention (KLIP) program. Thirty-two women were randomized into the control group or intervention group. The intervention group participated in 9 weeks (18 sessions) of the KLIP program, which involved proper landing techniques for jump-landing-jump tasks. The results of the study demonstrate that the KLIP program was able to reduce the ground reaction forces (which included peak impact forces and rate of force development at landing) during a step-land protocol. The authors concluded that reducing these peak forces during landing could reduce the risk of ACL injury.

The clinical effects of the KLIPP program, however, are still unproven. In 2006, a prospective two-year study was conducted by [41] to determine if the KLIPP program would reduce the risk of ACL injury. A total of 1,439 high school female athletes (playing soccer, basketball, and volleyball) were recruited from 15 schools (112 teams) for two consecutive seasons. A total of 862 students participated in the control group and 577 in the treatment group. The incidence of noncontact ACL injuries 0.167 in the treatment group and 0.078 in the control group yielded an odds ratio of 2.05, which was not statistically significant ($p > 0.05$).

1.3.2.6 FIFA 11+ Program

The Oslo Sports Trauma Research Center studied the effect of "The 11" program, a 15-min warm-up program for core stability, lower extremity strengthening, neuromuscular training, and agility. This was studied in a cluster randomized controlled study which included 1,091 female soccer players in the intervention group compared to 1,001 female soccer players in the control group [35]. A total of 396 (20 %) players sustained injuries. The authors noted no effect of the injury prevention program to decrease the injury rate; however, they noted that a significant portion of the intervention included soccer teams who did not complete most of the training sessions. In order to increase compliance with the program,



Figs. 1.3 and 1.4 Level 1: vertical jumps—*correct* landing and mid-air jump positions. Squat down until your hips and knees are bent to 90°.
Stay lowered for 2 s to make sure that your knees are not caved inward
Jump explosively into the air
Land gently on the balls of your feet with your hips and knees bent. Continue to squat and jump for 30 s (Figures were reprinted with permission from *The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury* published by Demos Health, 2012)

the Oslo researchers and FIFA collaborated to create the "FIFA 11+" program to improve both the preventive effect of the previous "11" program as well as the compliance of players and coaches. The revised program ("The 11+") provided variation and progression in its exercise selection, as well as a new set of structured running exercises suited better for a comprehensive warm-up program for training and matches. Soligard et al. [33, 34] reported using a cluster randomized trial that the players undergoing the "FIFA 11+" program had a significantly lower risk of overall injury, overuse injuries, and severe injuries compared to controls. In a recent randomized control trial [31], the FIFA 11+ has also been proven effective in reducing injuries among male collegiate soccer players. The injury rate was reduced by 46.1 %, and the time loss to injury decreased by 28.6 % in the competitive male collegiate soccer player. This was the first study to show success of a prevention program for male athletes.

1.4 Outcomes and Effectiveness of ACL Prevention Programs

Since 1990, 14 large-scale clinical trials with a variety of prevention programs (including those above) have been performed to determine the efficacy of ACL prevention programs. From these trials, several overarching strategies can be gleaned from their results. Evidence from these trials demonstrates that neuromuscular training programs are more effective in younger individuals. In a recent meta-analysis, Myer et al. [20]

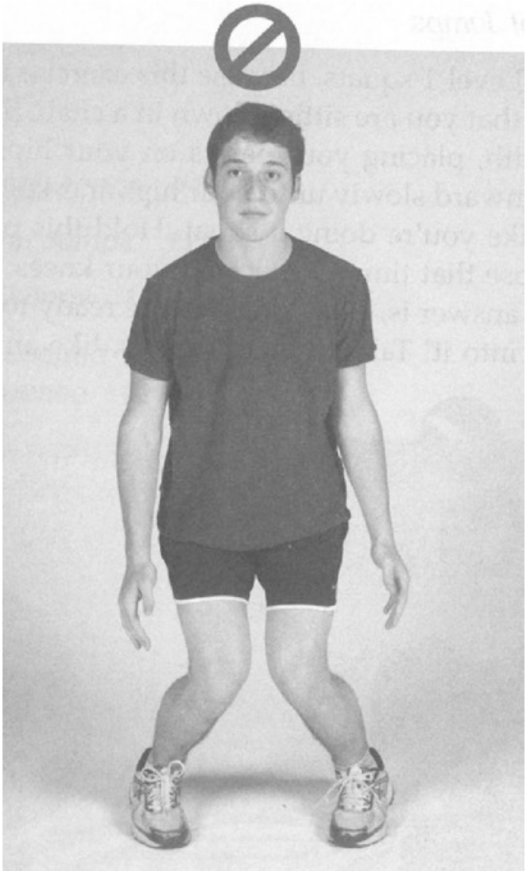


Fig. 1.5 Level 1: vertical jumps—*incorrect* knock-kneed landing position (Figures were reprinted with permission from *The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury* published by Demos Health, 2012)

compared the risk of female athletes undergoing neuromuscular training ages 14–18 and 19–20 to those aged 20 years and above as reference. The 14–18- and 19–20-year-old female athletes demonstrated a reduced risk of sustaining ACL injuries by 72 % and 52 %, respectively.

Increased compliance to any ACL prevention program is critical to the success of a prevention program. In a meta-analysis, Sugimoto et al. [37] demonstrated that with a compliance rate of greater than 66 %, an ACL injury reduction rate of 82 % was observed. However, when the compliance rate decreased to less than 66 % or 33 %, the rates of ACL injury reduction were found to be 44 % and 12 %, respectively. As one would expect, the success of any ACL program depends on participant adherence. The same analysis demonstrated an inverse dose response associated between program training volume and ACL injury: the more time athletes spent in their respective training programs, the fewer ACL injuries they sustained.

Finally, programs that consist of multiple different types of exercises demonstrated increased effectiveness. In a separate meta-analysis, Sugoimoto et al. [36] demonstrated that training programs with multiple types of exercises had greater reduction in incidence of ACL injury compared to those with only a single exercise modality. Given the multifactorial nature of ACL injuries, it makes sense that a successful ACL prevention program would incorporate a variety of exercises within neuromuscular training.

Financially, ACL prevention programs have been shown to be cost-effective, at least in theory. In 2014, [38] created a decision-analytic model that was created to compare the cost-effectiveness of either an ACL prevention program versus a screening program. They enrolled hypothetical cohort of young athletes into three groups: (1) no training/screening, (2) ACL prevention program, (3) screening for high-risk athletes and enrolling only high-risk athletes in ACL prevention program. They concluded that the universal implementation of an ACL prevention training program could save $100 per player per season and reduce the incidence of ACL injury from 3 % to 1.1 % per season.

Conclusions

ACL injuries continue to be a common knee injury despite a significant amount of research dedicated to its mechanism of action, risk factors, and prevention. Successful ACL injury prevention programs take on a multifaceted approach and combine a variety of neuromuscular and proprioceptive training exercises. Equally important is the dose-dependent effect of prevention programs: ideally, exercises should be performed year-round for maintenance. Ultimately, more efforts should be placed into educating coaches, parents, trainers, and physical therapists in addition to athletes themselves about risk factors associated with ACL injury and strategies to prevent them.

References

1. Bien DP (2011) Rationale and implementation of anterior cruciate ligament injury prevention warm-up programs in female athletes. J Strength Cond Res 25:271–285
2. Caraffa A, Cerulli G, Projetti M et al (1996) Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. Knee Surg Sports Traumatol Arthrosc 4(1):19–21
3. Ebben WP, Fauth ML, Petushek et al (2010) Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cuttings. J Strength Cond Res 24:405–415
4. Ford KR, Myer GD, Hewett TE (2003) Valgus knee motion during landing in high school female and male basketball players. Med Sci Sports Exerc 35(10):1745–1750
5. Gilchrist J, Mandelbaum BR, Melancon H et al (2008) A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med 36:1476–1483
6. Gomez E, DeLee JC, Farney WC (1996) Incidence of injury in Texas girls' high school basketball. Am J Sports Med 24:684–687
7. Grandstrand SL, Pfeiffer RP, Sabick MB et al (2006) The effects of a commercially available warm-up program on landing mechanics in female youth soccer players. J Strength Cond Res 20(2):331–335
8. Heidt RS Jr, Sweeterman LM, Carlonas RL et al (2000) Avoidance of soccer injuries with preseason conditioning. Am J Sports Med 28:659–662
9. Hewett TE, Ford KR, Hoogenbaum BJ et al (2007) Understanding and preventing ACL injuries: current biomechanical and epidemiologic consideration. Am J Sports Med 35(2):235–241
10. Hewett TE, Johnson DL (2010) ACL prevention programs: fact or fiction? Orthopedics 33:36–39
11. Hewett TE, Lindenfeld TN, Riccobene JV et al (1999) The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. Am J Sports Med 27:699–706
12. Hewett TE, Myer GD, Ford KR et al (2012) The 2012 ABJS Nicolas Andry aware the sequence of prevention: a systematic approach to prevent anterior cruciate ligament injury. Clin Orthop Relat Res 470:2930–2940
13. Hewett TE, Stroupe AL, Nance TA et al (1996) Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. Am J Sports Med 24:765–773
14. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, Krosshaug T (2010) Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med 38(11):2218–2225
15. LaBella CR, Huxford MR, Grissom J, Kim KY, Peng J, Christoffel KK (2011) Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. Arch Pediatr Adolesc Med 165(11):1033–1040
16. Ladenhauf HN, Graziano J, Marx RG (2013) Anterior cruciate ligament prevention strategies: are they effective in young athletes – current concepts and review of literature. Curr Opin Pediatr 25:64–71
17. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33:1003–1010
18. Marx RG, Mykleburst G, Boyle BW (2012) The ACL solution: prevention and recovery for sports' most devastating knee injury. Demos Medical Publishing, LLC, New York
19. McNair PJ, Marshall RN, Matheson JA (1990) Important features associated with acute anterior cruciate ligament injury. N Z Med J 103:537–539
20. Myer GD, Sugimoto D, Thomas S, Hewett TE (2012) The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. Am J Sports Med 41(1):203–215
21. Myklebust G, Engebretsen L, Braekken IH et al (2007) Prevention of noncontact anterior cruciate ligament injuries in elite and adolescent female team handball athletes. Instr Course Lect 56:407–418
22. Olsen OE, Myklebust G, Engebretsen L et al (2005) Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ 330:449
23. Padua DA, DiStefano LJ (2009) Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: a systematic review. Sports Health 1:165–173
24. Padua DA, Marshall SW (2006) Evidence supporting ACL-injury prevention exercise programs: a review of the literature. Athl Ther Today 11:11–23
25. Paterno MV, Rauh MJ, Schmitt LC et al (2012) Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. Clin J Sport Med 22:116–121
26. Paterno MV, Rauh MJ, Schmitt LC et al (2014) Incidence of second ACL injury after primary ACL reconstruction and return to sports. Am J Sports Med 42(7):1567–1573
27. Petersen W, Braun C, Bock W et al (2005) A controlled prospective case control study of a prevention

training program in female team handball players: the German experience. Arch Orthop Trauma Surg 125:614–621

28. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, Georgoulis T, Hewett TE, Johnson R, Krosshaug T, Mandelbaum B, Micheli L, Myklebust G, Roos E, Roos H, Schamasch P, Shultz S, Werner S, Wojtys E, Engebretsen L (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412
29. Shimokochi Y, Shultz SJ (2008) Mechanisms of non-contact anterior cruciate ligament injury. J Athl Train 43:396–408
30. Silvers HJ, Mandelbaum BR (2007) Prevention of anterior cruciate ligament injury in the female athlete. Br J Sports Med 41(Suppl 1):i52–i59
31. Silvers-Granelli H, Mandelbaum B, Adeniji O et al (2015) Efficacy of the FIFA 111 injury prevention program in the collegiate male soccer player. Am J Sports Med 43(11):2628–2637
32. Soderman K, Werner S, Pietilla T et al (2000) Balance board training: prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. Knee Surg Sports Traumatol Arthrosc 8:356–363. doi:10.1007/s001670000147
33. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, Andersen TE (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469. doi:10.1136/bmj.a2469
34. Soligard T, Myklebust G, Steffen K et al (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: controlled trial. BMJ 337:a2469
35. Steffen K, Myklebust G, Olsen OE, Holme I, Bahr R (2008) Preventing injuries in female youth football—a cluster-randomized controlled trial. Scand J Med Sci Sports 18(5):605–614. doi:10.1111/j.1600-0838.2007.00703.x
36. Sugimoto D, Myer GD, Barber Foss KD, Hewett TE (2014) Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. Br J Sports Med. doi:10.1136/bjsports-2014-093461
37. Sugimoto D, Myer GD, Bush HM, Klugman MF, Medina McKeon JM, Hewett TE (2012) Compliance with neuromuscular training and anterior cruciate ligament injury risk reduction in female athletes: a meta-analysis. J Athl Train 47(6):714–723
38. Swart E, Redler L, Fabricant PD, Mandelbaum BR, Ahmad CS, Wang YC (2014) Prevention and screening programs for anterior cruciate ligament injuries in young athletes: a cost-effectiveness analysis. J Bone Joint Surg Am 96(9):705–711. doi:10.2106/JBJS.M.00560
39. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, Krosshaug T (2010) Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med 38(11):2218–2225. doi: 10.1177/0363546510373570
40. Quatman CE, Hewett TE (2009) The anterior cruciate ligament injury controversy: is valgus collapse a sex-specific mechanism? Br J Sports Med 43(5):328–335
41. Pfeiffer RP, Shea KG, Roberts D, Grandstrand S, Bond L (2006) Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. J Bone Joint Surg Am 88(8):1769–1774

Arthroscopic Setup for ACL Reconstruction

2

Mark Miller, Riccardo Compagnoni,
and Pietro Randelli

2.1 Introduction

Knee arthroscopy is the most commonly performed orthopedic procedure. Indications include diagnostic arthroscopy, meniscectomy, loose body removal, chondroplasty, microfracture, irrigation and debridement, and ligament reconstruction. Correct patient setup is crucial for performing a safe and effective operation. As with many other aspects of surgery, there are many different options for patient preparation and positioning. In this entry the authors will try to describe the most common and reproducible techniques. Only few articles are available in literature that discusses aspects of patients' positioning, but book chapters and the recent introduction of high quality online videos are now available to orthopedic surgeons. The aim of this entry is to provide an up-to-date description of patient preparation to permit the execution of an effective procedure, beginning with anesthesia through the initiation of the surgical case.

2.2 Anesthesia

The selection of anesthesia is a major decision that could have a significant impact on recovery. It deserves careful consideration, and a comprehensive discussion between the patient and anesthesiologist is crucial for a patient-specific procedure. Many parameters must be considered, but the most important are previous reactions to anesthesia, patient's current health and physical condition, and all allergies or adverse side effects from any drugs. The most common types of anesthesia are local anesthesia, regional anesthesia, spinal block, epidural block, and peripheral nerve block.

Local anesthesia affects only the specific area being treated. The area is numbed with an injection, spray or ointment that lasts only for a short period of time. Patients remain conscious during this type of anesthesia. This technique is reserved for minor procedures. For major surgery, such as hip or knee replacement, local anesthesia may be used to complement the main type of anesthesia that is used. Local anesthesia is not frequently used for arthroscopic operative procedures due to concern that it may take longer to perform the surgery and that the anesthesia will be inadequate, leading to patient

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discomfort. Additionally, patients may unexpectedly move, and this could result in an iatrogenic injury. Nevertheless, some studies report results similar to other forms of anesthesia and a low rate of patient discomfort [1, 2].

2.3 Regional Anesthesia

Regional anesthesia involves blocking the nerves to a specific area of the body, without affecting the central nervous system or pulmonary system. The patients are often given sedatives to relax and put them into a light sleep. The three types of regional anesthesia used most frequently in knee arthroscopy are spinal blocks, epidural blocks, and peripheral nerve blocks. In a spinal block, the anesthesia is injected into the thecal sac surrounding the spinal. This produces a rapid numbing effect that wears off after several hours. Epidural block involves placing a catheter outside the thecal sac in order to deliver local anesthetics over a variable period of time (Fig. 2.1).

Peripheral nerve blocks place local anesthetic directly around the major nerves in the thigh, such as the femoral nerve or the sciatic nerve. These blocks numb only the extremity that is injected. One option for a peripheral block is to perform a one-time injection around the nerves in order to numb the extremity just long enough for the surgery. Another option for this type of block is to keep a catheter in place, which can deliver continuous local anesthesia around the nerves for up to several days after surgery. Regional anesthesia has many advantages, including causing less nausea and drowsiness, improved pain control after surgery, and reduced risk of serious medical complication that may occur with general anesthesia.

2.4 General Anesthesia

General anesthesia is often used for major surgery, such as a joint replacement, but in some centers it is used also for knee ligamentous reconstruction. General anesthesia may be selected based on patient, surgeon, or anesthesiologist preference or if the patient is unable to receive regional or local anesthesia. With general anesthesia, the anesthesiologist administers medication through injection or inhalation. The anesthesiologist will also place an endotracheal or laryngeal tube in the throat and administer

Fig. 2.1 Anesthesiologist performing spinal block

oxygen to assist breathing. General anesthesia affects both heart and breathing rates, and there is a very small risk of serious medical complications, such as heart attack or stroke.

2.5 Prophylactic Antibiotics

Knee arthroscopies have a very low rate of infective complication when only a diagnostic procedure or a simple meniscectomy is performed, and according to the recent literature, there is no evidence of usefulness of antibiotics in these simple procedures. Bert et al. reported an infection rate of 0.15 % when prophylactic antibiotics were used compared to 0.16 % in patients who underwent surgery without an antibiotic prophylaxis. Infection is a relatively rare but potentially serious complication after anterior cruciate ligament reconstruction. Many risk factors have been described, including smoking, obesity, and diabetes. Antibiotic prophylaxis appears to be the safest way to prevent postsurgical infections. In many hospitals 2 g of a second-generation cephalosporin is used with a significant reduction of infective rates [3–5].

2.6 Thromboprophylaxis

Incidence of venous thromboembolism after arthroscopic ACL reconstruction is described in literature with a percentage between 1.7 and 4 %. In clinical practice different protocols are used ranging from nothing to low molecular weight heparin in all patients. Further research is recommended to assess the need for thromboprophylaxis in patients undergoing ACL reconstruction, especially when risk factors are present [6, 7].

2.7 Patient Positioning

Patient positioning is a crucial part of surgery, and incorrect placement can result in prolonged surgical times and unexpected complications. Patient positioning is variable, based upon surgeon's habits and the instruments available in the operating theater. There are a few important concepts that we will highlight that may make procedures fast and efficient.

The patient is positioned with the heels at the end of the table for easy access and manipulation. The pelvis is moved on the side of the bed on the side of surgery, with the trochanteric region on the border of the surgical bed. A good practice is to position a safety belt well attached to the bed, at pelvis level, to block the patient from unexpected movements.

Depending on the surgeon's preference, a tourniquet is positioned high on the thigh to permit a comfortable surgical field preparation and avoid distal migration of it. The tourniquet must be placed snug but not tight. Before positioning the tourniquet a soft cotton padding material is rolled on. The tourniquet pressure is usually set between 300 and 350 mm/hg for a normal adult man or female and is activated when the sterile field is ready. Many articles have been written about tourniquet usefulness in arthroscopic surgery. Arthroscopic anterior cruciate ligament reconstruction with a tourniquet was significantly associated with less operative visualization difficulties ($p < 0.05$), compared with surgery without a tourniquet. There were no significant differences in visual analogue scale pain, blood loss, operation time, and complications between the two groups as evidenced by many studies [8, 9]. One recent study demonstrated that tourniquet use did not affect rehabilitation, return to activities, and muscle damage after arthroscopic meniscectomy [10].

After the positioning of tourniquet, a plastic drape can be placed to protect the tourniquet and the patient from the preparation solution. After this step there are two different options for preparing the patient, using the circumferential leg holder or a lateral post. In the first case the leg holder is attached close to the thigh, the strap is placed, and the foot of the bed is lowered or removed depending on the table type. The surgeon or an assistant must check that the leg can be moved to obtain a correct visualization of the medial and lateral compartments of the knee. If the surgeon works without an assistant, the leg can be positioned in valgus for medial arthroscopy or (Fig. 2.4) for lateral arthroscopy.

Some surgeons prefer a lateral post instead of a leg holder (Fig. 2.2). Posts are available in many designs, curved or flat, fixed or with a small rotational movement. The post can be removed, and the leg flexed down the side of the table in order to perform surgery of the intercondylar notch. The lateral compartment is well exposed, positioning the leg in a four position, with the foot positioned across the contralateral leg and the knee flexed at 90°. Additional force can be applied to the medial knee to further open the lateral compartment.

2.8 Instruments

The arthroscopic tower is positioned on the opposite site of the operative leg, in front of the surgeon to permit a correct view. The tower must include a high-definition screen, a powered shaver system, a fluid management system to maintain a stable fluid pressure inside the knee, an ablation system, and a foot switch system, which is available on the market in a wireless version as well. In the past operating theater, lights were turned off partially to permit an optimal view, but with new screens this is usually not necessary for knee arthroscopy. If patient viewing is desired, the screen and drapes can be adjusted accordingly. Modern systems have the function of recording the images and videos during surgery and saving them in mobile devices through USB key or electronic tablets, permitting to show at the patients the images the days after surgery or organize a database in surgeon's personal archive.

ACL reconstruction requires specific surgical devices to perform a correct procedure. A large variety of arthroscopic handheld instruments are commercially available on the market, depending on the desires of each surgeon. A 30° arthroscope is most commonly used by knee surgeons, but many different angulations are available for specific pathologies. Different basket punches are available on the market with a broad range of tips and configurations allowing access to specific areas of the meniscus. A shaver connected to the tower is useful in preparing the intercondylar notch inside of origin of the ACL and partially removes the Hoffa fat pad. Cannulated reamers of different sizes must be on the back table for creating the tibial and femoral tunnels. Fixation systems for the tibia and femur and must be in sight and a check of having all equip-

Fig. 2.2 Patient positioning using the lateral post

ment and instruments prior to starting surgery. A meniscal suture system should be in the operating theater as well in case of an unexpected meniscal repair.

2.9 Operating Field

Full aseptic precautions must be taken, and the skin should be shaved, and a standard antiseptic solution such as a chlorhexidine-based solution or a povidone-iodine should be applied on the entire leg. Special precautions should be taken when dealing with the skin around the foot as the bacterial load is high and the risk of cross contamination of the operative site is greater [5]. An elastic stockinette can be used to cover the foot after disinfection and protect the leg from contamination (Fig. 2.3).

Knee arthroscopy requires a draping system that maintains a sterile field throughout the procedure and reliably adheres to the skin to reduce the likelihood of drapes moving over long period of times. Heavy manipulation often occurs during orthopedic procedures, and drapes need to be able to withstand this. An adequate surgical drape must effectively control and contain fluid, to avoid risk of infections and to keep the patient dry. A commonly used drape has an opening that can be passed through the foot reaching the middle of the thigh just distal to the tourniquet and a pouch is used to collect water and fluids to avoid water dripping on the floor of the operating theater [11] (Figs. 2.4 and 2.5). The arthroscopy portals, patellar tendon, and skin incisions are marked on the skin with a marking pen (Figs. 2.5 and 2.6). Anterolateral

Fig. 2.3 Full aseptic precautions must be taken, the skin should be shaved, and a standard antiseptic solution such as a chlorhexidine-based solution or a povidone-iodine should be applied on the entire leg. Special precautions should be taken when dealing with the skin around the foot

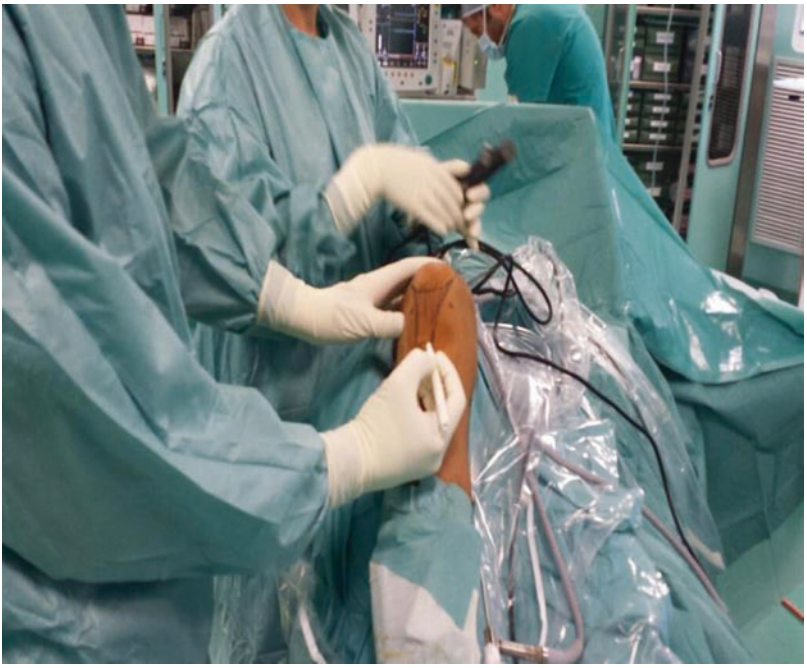

Fig. 2.4 The arthroscopy portals, patellar tendon, and skin incisions are marked on the skin with a marking pen

Fig. 2.5 Final patient positioning for ACL reconstruction with lateral post

Fig. 2.6 Patient positioning using the circumferential leg holder

portal is placed at the level of the inferior and lateral edge of the patella, at least 1 cm above the lateral joint line and 1 cm lateral to the margin of the patellar tendon. The anteromedial portal is placed similar to the lateral one, 1 cm medial to the patellar tendon and above the joint line. The use of a spinal needle can help the surgeon to find the correct entry point. The posteromedial portal is used in complex meniscal and cartilage repair procedures and is located in the soft spot formed by the posteromedial edge of the medial condyle and the posteromedial edge of the tibia. After the preparation of the field, arthroscopic instruments are connected to the arthroscopic tower maintaining the sterility, using dedicated protections available on the market. Following appropriate positioning and draping, a formal "time-out" is done and the procedure can begin.

References

1. Shaukat Y, Malik E, El-Khateeb H, Koeweiden E (2013) The role of local anaesthesia in knee arthroscopy. J Orthop 10(4):193–195. doi:10.1016/j.jor.2013.06.003
2. Forssblad M, Weidenhielm L (1999) Knee arthroscopy in local versus general anaesthesia. The incidence of rearthroscopy. Knee Surg Sports Traumatol Arthrosc 7(5):323–326
3. Bert JM, Giannini D, Nace L (2007) Antibiotics prophylaxis for arthroscopy of the knee: is it necessary? Arthrosc J Arthrosc Relat Surg 23(1):4–6
4. Brophy RH, Wright RW, Huston LJ, Nwosu SK, Splinder KP (2015) Factors associated with infection following anterior cruciate ligament reconstruction. J Bone Joint Surg Am 97(6):450–454
5. Ghnaimat MM, Shawabkeh JS, Hijazi AM, Alturk MM, Aldweri M (2009) Is antibiotic prophylaxis in knee arthroscopy mandatory? J R Med Serv 16(2):39–41
6. Struijk-Mulder MC, Ettema HB, Verheyen CC, Buller HR (2013) Deep vein thrombosis after arthroscopic anterior cruciate ligament reconstruction:

a prospective cohort study of 100 patients. Arthroscopy 29(7):1211–1216

7. Adala R, Anand A, Kodikal G (2011) Deep vein thrombosis and thromboprophylaxis in arthroscopic anterior cruciate ligament reconstruction. Indian J Orthop 45(5):450–453
8. Smith T, Hing CB (2009) A meta-analysis of tourniquet assisted arthroscopic knee surgery. Knee 16(5):317–321. doi:10.1016/j.knee.2009.01.004
9. Hoogeslag RA, Brouwer RW, van Raay JJ (2010) The value of tourniquet use for visibility during arthroscopy of the knee: a double-blind, randomized controlled trial. Arthroscopy 26(9 Suppl):S67–S72. doi:10.1016/j.arthro.2009.12.008
10. Williams A (2013) Tourniquet use did not adversely affect recovery after arthroscopic meniscectomy. J Bone Joint Surg Am 95(16):1514. doi:10.2106/JBJS.9516.ebo339
11. Onyema C, Oragui E, White J, Khan WS (2011) Evidence-based practice in arthroscopic knee surgery. J Perioper Pract 21(4):128–134

3

Early vs. Delayed ACL Reconstruction "Early" Anterior Cruciate Ligament Reconstruction

Iftach Hetsroni and Robert G. Marx

3.1 Introduction

Despite increasing knowledge of anterior cruciate ligament (ACL) anatomy and improved surgical techniques for ACL reconstruction, uncertainty still remains regarding optimal timing for surgery in individuals [2]. The decision to perform ACL reconstruction early after the injury is affected by multiple factors. Risks of performing reconstruction early are related to the development of arthrofibrosis [4, 12, 17, 19] with longer rehabilitation periods and potentially operating on some patients that may recover normal knee laxity without surgery [8]. On the other hand, not performing ACL reconstruction within a short time after the injury has the potential for further meniscus and cartilage injuries [5, 6]. Timing of surgery could also be affected by cost-effectiveness considerations [11] and by demands to return as early as possible to sports in professional athletes. In this chapter, aspects of early ACL reconstruction will be discussed with focus on the association between timing of surgery and risk of arthrofibrosis, reinjury to the menisci and articular cartilage, as well as economic considerations.

3.2 Arthrofibrosis

Arthrofibrosis has been recognized as an adverse outcome after ACL reconstruction [4, 17, 19] and a major factor associated with patient dissatisfaction [10]. While multiple factors are associated with this outcome, time interval from injury to ACL reconstruction has been pointed out by several investigators as a leading risk factor (Table 3.1). Shelbourne et al. [17] originally reported in a retrospective analysis of 169 autologous BPTB ACL reconstructions in young athletes that patients who had surgery within the first week or between 8 and 21 days from the injury had significantly increased incidence of arthrofibrosis compared to patients who had their ligament reconstruction at more than 3 weeks from the injury (i.e., up to 17 % vs. 0 %, respectively). Of note, follow-up time was 3 months only. It should be noticed, however, that in cases where ACL reconstruction was performed between 8 and 21 days from the injury, accelerated postoperative rehabilitation program resulted in substantial decrease in the incidence of arthrofibrosis.

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Table 3.1 Characteristics and findings of studies investigating arthrofibrosis incidence after “early” ACL reconstruction

Lead author	Design	“Early” ACLR time frame definition	Graft source	Arthrofibrosis incidence “early” vs. “late” ACLR	Other clinical outcomes “early” vs. “late” ACLR	Follow-up time	Comments
Shelbourne et al. [17]	Retrospective analysis	Within 3 weeks	Autologous BPTB graft	Up to 17 % vs. 0 % $P<0.05$	Isokinetic test at 3M, Cybex score 50 % vs. 70 %, $P<0.05$	Reported up to 3 months	Accelerated postoperative rehabilitation program substantially decreased the incidence of arthrofibrosis
Wasilewski et al. [19]	Retrospective analysis	Within 1 month	Autologous STG graft + ITB tenodesis	22 % vs. less than 12.5 % $P<0.05$	Isokinetic test at 6M, quad torque 60 % vs. 74 %, $P<0.05$	Reported up to 18 months	Recovery after acute ACLR was significantly slower
Cosgarea et al. [4]	Retrospective analysis	Within 3 weeks	Autologous BPTB graft	21 % vs. 9 %, $P<0.05$	NR	1 year	Arthrofibrosis also associated with decrease in ROM before surgery, and immediate full extension postoperatively significantly reduced the risk of arthrofibrosis
Mayr et al. [12]	Retrospective analysis	Within 4 weeks	Autologous BPTB used in 75 % of cases	Unclear, but states that incidence significantly higher in “early” ACLR $P<0.001$	NR	Mean 4.29 years	Arthrofibrosis associated with “early” surgery, but even more with irritated knee and with decreased ROM before surgery
Meighan et al. [13]	Prospective randomized	Within 2 weeks	Autologous STG graft	7.6 % vs. 5.6 %, P = NS	IKDC, Lysholm, Tegner, quadriceps and hamstrings power and torque, $P = NS$	1 year	Identical postoperative rehabilitation programs for “early” and “late” ACLR
Botoni et al. [2]	Prospective randomized	Within 17 days	Autologous STG graft	3 % vs. 6 % with loss of 5–10° extension, P = NS 15 % vs. 14 % with loss of 5–10° flexion, P = NS	SANE, Lysholm, Tegner, P = NS	Mean 1 year	Identical postoperative rehabilitation programs for “early” and “late” ACLR

Smith et al. [18]	Meta-analysis of 6 studies	Within 1 month	Autologous BPTB or autologous GST grafts	Loss of >10° extension, $P = \text{NS}$ Loss of flexion, $P = \text{NS}$	Lysholm, Tegner, IKDC, HSS, return to sports $P = \text{NS}$	Variable among studies	Appraised the methodological limitations in previous investigations, such as limited statistical power, lack of prospectively randomized collected data, and others
Nwachukwu et al. [16]	Retrospective analysis	Within 1 month	BPTB or GST autografts in 86 % of cases	10 % vs. 8.2 %, $P = \text{NS}$	NR	Mean 6.3 years	Study population age 7–18 years. Risk factors for arthrofibrosis included older adolescents, female sex, BPTB autograft, and concurrent meniscal repair

Inferior outcomes were observed in the “early” reconstruction group also in regard to strength isokinetic tests. The authors concluded that delaying ACL reconstruction at least 3 weeks from the injury will result in earlier return to strength and in significantly decreased incidence of arthrofibrosis. These outcomes were reproduced by Wasilewski et al. [19] who performed a retrospective analysis of 87 autologous hamstrings ACL reconstructions with concomitant ITB tenodesis who were divided into three groups based on timing of surgery. Follow-up was reported up to 18 months. They showed that arthrofibrosis was found in 22 % of reconstructions performed within 1 month from injury compared to 0 % when reconstruction was performed between 1 and 6 months or 12.5 % when reconstruction was performed after 6 months from injury. They also showed inferior Quadriceps torque in the “early” reconstructions. Of note, the standard rehabilitation protocol used in their study mandated substantial motion limitations and included immobilization at 30° knee flexion for 7–10 days postoperatively, followed by braced motion from 20 to 60° for a few additional weeks. They also pointed out that recovery after ACL reconstruction performed within 1 month from injury was significantly slower compared to recovery when reconstruction was performed later than 1 month from injury.

Cosgarea et al. [4] performed a retrospective analysis of 191 consecutive autologous BPTB ACL reconstructions and similarly to Shelbourne et al. [17] and Wasilewski et al. [19] showed that surgery performed within the first 3 weeks of injury had significantly higher incidence of arthrofibrosis compared to surgery performed later than 3 weeks from injury (21 % vs. 9 %, respectively). However, an important finding of their study was that incidence of arthrofibrosis decreased from more than 20 % to less than 3 % when postoperative rehabilitation protocol was changed from bracing in 45° flexion for 7 days before the initiation of passive extension to bracing in full extension immediately after surgery. They therefore concluded that although surgery within 3 weeks from injury may place a knee at increased risk for arthrofibrosis, postoperative splinting in full extension with immediate protected weightbearing ambulation rather than splinting the knee in flexion position is the single most important factor in preventing arthrofibrosis.

Mayr et al. [12] performed a retrospective analysis of risk factors for arthrofibrosis after ACL reconstruction in 223 patients, 75 % of which had their reconstruction with autologous BPTB graft. They also demonstrated that incidence of arthrofibrosis was increased in cases where reconstruction was performed within 4 weeks from injury, but that irritated knee (swelling, effusion, hyperthermia) and lack of full ROM before surgery were more important risk factors for the development of arthrofibrosis than time interval from injury to surgery. In other words, when surgery was performed later than 4 weeks from injury but the knee was irritated, there was as increased risk for the development of arthrofibrosis compared to when surgery was performed within the first 4 weeks from the injury.

The first prospective randomized clinical trial that investigated the incidence of arthrofibrosis in “early” versus “delayed” ACL reconstruction was performed by Meighan et al. [13]. They studied a small series of athletic patients that underwent ACL reconstruction using autologous quadrupled hamstrings graft and used similar postoperative rehabilitation protocols for both groups. The “early” reconstruction group had surgery within 2 weeks from injury, and the “delayed” group had surgery between 8 and 12 weeks from injury. Although loss of knee motion was more pronounced at 2 weeks after the operation in the “early” group, at 1-year follow-up, there were no differences in knee motion, nor there were differences between the groups in relation to IKDC, Lysholm, and Tegner scores and examination of quadriceps and hamstrings muscle power and torque.

Bottoni et al. [2] performed another prospective clinical trial for the same purpose using a larger sample. The reconstructions were performed with autologous hamstring autograft. “Early” reconstruction patients had their surgery within the first 17 days after the injury, and “late” reconstruction patients had their surgery at 6 or more weeks after the injury. Both reconstruction groups followed similar supervised rehabilitation protocols with early mobilization and emphasis on maintenance of extension. The investigators found comparable knee flexion and extension in both groups. Furthermore, no clinical differences were observed between the two groups in relation to knee stability and Lysholm and Tegner scores. The authors concluded that delaying surgery for some arbitrary period of time due to the concern of increased risk of arthrofibrosis is not necessary, although they did not recommend performing ACL reconstruction acutely.

The outcomes of "early" versus "delayed" ACL reconstruction were also investigated in a systematic review and meta-analysis by Smith et al. [18]. There were overall six studies fulfilling inclusion criteria in which ACL reconstructions were performed with either autologous patellar tendon or hamstring grafts. "Early" reconstruction was considered surgery performed within 1 month from the injury. This meta-analysis could not identify any significant differences in the incidence of arthrofibrosis or in any functional outcome score or activity level outcome scores between reconstructions performed "early" compared to those performed "late." Of note, the authors noted the methodological limitations in previous investigations, including limited statistical power and lack of sufficient prospective, randomized data.

Arthrofibrosis after ACL reconstruction in young patients, aged 7–18 years old, was investigated by Nwachukwu et al. [16]. A retrospective analysis of more than 900 ACL reconstructions performed with autologous patellar tendon or hamstring grafts in almost 90 % of the cases showed no difference in the incidence of arthrofibrosis between surgery performed within 1 month from injury and surgery performed later. On the other hand, positive risk factors for the development of arthrofibrosis included older adolescents, female sex, the use of patellar tendon autograft, and concurrent meniscal repair. In summary, while risk of arthrofibrosis may be increased when ACL reconstruction is performed within less than a month from injury compared to later than a month, it seems that this risk can be significantly reduced by avoiding reconstruction in knees with limited ROM and when marked swelling and effusion persist. In addition, early ROM exercises with immediate maintenance of full extension after early reconstruction is likely paramount in this respect as well.

3.3 Reinjury to Menisci and Articular Cartilage

Studies have demonstrated that after acute ACL tear in young active adults, reconstruction rather than nonoperative management decreased the risk of reoperation due to subsequent meniscal and chondral injuries [5, 6]. Dunn et al. [5] showed in a retrospective cohort study of 6,576 active army personnel who were hospitalized after acute ACL injury that ACL reconstruction decreased the risk of a subsequent meniscal reoperation by half and subsequent cartilage reoperation by a third compared with those not reconstructed. However, while this large cohort study provided justification for performing ACL reconstruction in young active adults to reduce the risk of subsequent reoperation, it did not investigate the optimal timing for surgery to achieve this goal. Moreover, definitions of "early" ACL reconstruction in relation to reducing the risk for subsequent meniscal or chondral injuries remain somewhat unclear. Church and Keating [3] reviewed 183 patients who had ACL reconstruction and studied the association between meniscal and chondral lesions and timing from injury to surgery. Their cutoff line for "early" as opposed to "delayed" reconstruction was at 12 months from the injury. In this retrospective review, a significantly higher incidence of meniscal tears, primarily medial meniscus, and chondral lesions was found in the "delayed" group compared to the "early" group (71 % vs. 42 % for meniscal tears and 31 % vs. 11 % for chondral lesions, $p < 0.01$). The authors concluded that reconstruction of the ACL should be performed within 12 months from the injury to reduce the risk of meniscal tears and degenerative changes.

Another retrospective analysis that advocated reconstruction of the ACL within 1 year to minimize the risk of medial meniscus tears was reported by Kennedy et al. [9]. They used a larger cohort of 300 athletic patients and showed that meniscal injury was eight times more common when reconstruction was performed after 1 year compared to within 1 year from injury. Moreover, the risk of degenerative changes in the knee was four times higher when surgery was performed after 6 months from injury compared to before 6 months. The timing of ACL reconstruction in relation to the risk of meniscal and chondral injuries was also studied as a continuous variable. In a large population-based cohort study by Granan et al. [7], the Norwegian National Knee Ligament Registry was used to review 3,475 knees. They have found that the odds for a cartilage lesion in the adult knee was increased by nearly 1 % for each month that elapsed from the injury until surgery and that cartilage lesions were nearly twice as frequent if there was a meniscal tear and vice versa. This study showed that reconstruction of the ACL is preferably performed sooner than later to minimize the risk for subsequent associated injuries but without setting a specific point in time from the injury as a "best" cutoff line.

Several investigators reported on the association between timing of surgery and the incidence of associated meniscal and chondral injuries specifically in children and adolescents. Millett et al. [14] reviewed a small cohort of 39 patients with age range of 10–14 years who had ACL reconstruction. "Acute" reconstruction was defined as performed within 6 weeks from injury and "chronic" as performed after 6 weeks. Medial meniscus tears were highly associated with time from injury to surgery ($p=0.02$). Lateral meniscus tears were not associated with time of surgery. Furthermore, medial meniscus tears were more common in the "chronic" group (36 %) than in the "acute" group (11 %), but lateral meniscus tears were found in equal frequency. Anderson and Anderson [1] reviewed a much larger cohort of 135 ACL reconstructions in patients younger than 17 years. "Acute" reconstruction was defined as performed within 6 weeks from injury and "chronic" as performed later than 3 months. They not only investigated the correlation between meniscal and chondral injuries and timing of reconstruction, but they have also further defined the severity of meniscal tears and their association with episodes of instability and with return to sports before surgery. They have found that both medial and lateral meniscus tears were associated with time to surgery. Any episode of instability increased the incidence of medial and lateral meniscus tears by three- to fourfold. Return to sports before reconstruction increased the incidence of lateral meniscus tears. Increased severity of medial meniscus tear was associated with playing sports before reconstruction (adjusted OR = 15.2, $p<0.01$), any episode of instability (adjusted OR = 5.6, $p<0.01$) and time to surgery greater than 3 months (adjusted OR = 4.3, $p<0.05$). Risk factors for chondral injury included increased time to surgery and any instability episode. Newman et al. [15] supported these findings and demonstrated that a delay in ACL reconstruction for more than 3 months in young populations was a strong predictor for meniscal injury and chondral injury.

In summary, it seems that delaying ACL reconstruction is associated with an increase in meniscal and chondral lesions as a general rule, and in this sense "early" reconstruction may be preferable to "delayed" reconstruction. It is however unknown whether there is a specific point in time that should not be passed in order to decrease this risk of associated injuries or whether avoiding returning to sports before surgery and implementing activity modification strategy is a better method to decrease the risk of subsequent knee injury than timing per se. In children and adolescents, it seems that time frame from injury to ACL reconstruction should probably be minimized to several weeks or a maximum of 3 months in order to decrease associated meniscal and chondral injuries, and this may be due to the fact that activity levels can rarely be controlled in very young and active populations, and thus further knee instability is common, leading to subsequent medial meniscus tears.

3.4 Economic Considerations

Timing of ACL reconstruction has also been linked to economic considerations. Mather et al. [11] performed cost-effectiveness analysis of early versus delayed ACL reconstruction, using two primary sources of data: Short-Form-36 outcome score of the prospective cohort of primary ACL reconstruction from the Multicenter Orthopedic Outcome Network (MOON) and the knee anterior cruciate ligament, nonsurgical versus surgical treatment (KANON) study by Frobell et al. [6] that compared prospectively the outcomes of early ACL reconstruction (within less than 10 weeks) versus rehabilitation and optional delayed reconstruction. They found that the cost of rehabilitation and the rate of additional surgery for meniscus tears were responsible for increased cost of the delayed optional ACL reconstruction compared to early ACL reconstruction. The most sensitive variable was the rate of knee instability after initial rehabilitation. Less instability was associated with less cost. In this respect, and in accordance with this finding, it is worth noticing that although Frobell et al. [6] found no significant differences between their two groups at 2-year follow-up as determined by total KOOS, they did not perform cost-effectiveness analyses. The group with optional delayed reconstruction in their study demonstrated a high crossover rate (nearly 40 % at 2 years and over 50 % at 5 years) and clinical instability (over 30 %) at 2 years compared to very little instability (3 %) in the early ACL reconstruction group. Moreover, two thirds of the patients that did not have ACL reconstruction underwent knee arthroscopy to treat meniscus tears. These data explain how early ACL reconstruction accounts for higher cost-effectiveness compared to long rehabilitation with delayed optional reconstruction in young, active patients in the study by Mather et al. [11]. From a societal health system economic perspective, early ACL reconstruction, without waiting for symptomatic instability or subsequent meniscal tears to develop, is therefore the preferred treatment strategy.

3.5 Summary

The definition of "early" reconstruction varies among studies. Viewing the risk of arthrofibrosis, it seems that most authors draw the cutoff line between 3 and 4 weeks from the injury. In this regard, although historically it was suggested in retrospective analyses that early reconstruction was a significant risk factor for this adverse outcome, recent studies and prospective randomized controlled trials showed that performing reconstruction in a knee without swelling, effusion, hyperthermia, and lack of motion and also implementing immediate ROM exercises with maintenance of full extension after surgery likely decrease the risk. In view of the risk of meniscal and chondral injuries, early reconstruction is preferred to delayed surgery. We feel early reconstruction applies to the first 2–3 months after injury during which cutting and pivoting sports activities should be avoided. In terms of societal economic considerations, early reconstruction in young active individuals is advantageous compared to long rehabilitation periods with optional delayed reconstruction which exposes patients to recurrent episodes of instability and subsequent meniscal tears, which may require more surgery.

References

1. Anderson AF, Anderson CN (2014) Correlation of meniscal and articular cartilage injuries in children and adolescents with timing of anterior cruciate ligament reconstruction. Am J Sports Med 43:275–281
2. Bottoni CR, Liddell TR, Trainor TJ, Freccero DM, Lindell KK (2008) Postoperative range of motion following anterior cruciate ligament reconstruction using autograft hamstrings. A prospective randomized clinical trial of early versus delayed reconstructions. Am J Sports Med 36:656–662
3. Church S, Keating JF (2005) Reconstruction of the anterior cruciate ligament: timing of surgery and the incidence of meniscal tears and degenerative change. J Bone Joint Surg Br 87:1639–1642
4. Cosgarea AJ, Sebastianelli WJ, DeHaven KE (1995) Prevention of arthrofibrosis after anterior cruciate ligament reconstruction using the central third patellar tendon autograft. Am J Sports Med 23:87–92
5. Dunn WR, Lyman S, Lincoln AE, Amoroso PJ, Wickiewicz T, Marx RG (2004) The effect of anterior

cruciate ligament reconstruction on the of knee reinjury. Am J Sports Med 32:1906–1914

6. Frobell RB, Roos EM, Roos HP, Ranstam J, Lohmander LS (2010) A randomized trial of treatment for acute anterior cruciate ligament tears. N Engl J Med 363:331–342
7. Granan LP, Bahr R, Lie SA, Engebretsen L (2009) Timing of anterior cruciate ligament reconstructive surgery and risk of cartilage lesions and meniscal tears: a cohort study based on the Norwegian National Knee Ligament Registry. Am J Sports Med 37:955–961
8. Hetsroni I, Delos D, Fives G, Boyle BW, Lillemoe K, Marx RG (2013) Nonoperative treatment for anterior cruciate ligament injury in recreational alpine skiers. Knee Surg Sports Traumatol Arthrosc 21:1910–1914
9. Kennedy J, Jackson MP, O'kelly P, Moran R (2010) Timing of reconstruction of the anterior cruciate ligament in athletes and the incidence of secondary pathology within the knee. J Bone Joint Surg Br 92:362–366
10. Kocher MS, Steadman JR, Briggs K et al (2002) Determinants of patient satisfaction with outcome after anterior cruciate ligament reconstruction. J Bone Surg Am 84:1560–1572
11. Mather RC 3rd, Hettrich CM, Dunn WR, Cole BJ, Bach BR Jr, Huston LJ, Reinke EK, Spindler KP (2014) Cost-effectiveness analysis of early reconstruction versus rehabilitation and delayed reconstruction for anterior cruciate ligament tears. Am J Sports Med 42:1583–1591
12. Mayr HO, Weig TG, Plitz W (2004) Arthrofibrosis following ACL reconstruction – reasons and outcome. Arch Orthop Trauma Surg 124:518–522
13. Meighan AA, Keating JF, Will E (2003) Outcome after reconstruction of the anterior cruciate ligament in athletic patients. A comparison of early versus delayed surgery. J Bone Joint Surg Br 85:521–524
14. Millett PJ, Willis AA, Warren RF (2002) Associated injuries in pediatric and adolescent anterior cruciate ligament tears: does a delay in treatment increase the risk of meniscal tear? Arthroscopy 18:955–959
15. Newman JT, Carry PM, Terhune EB, Spruiell MD, Heare A, Mayo M, Vidal AF (2014) Factors predictive of concomitant injuries among children and adolescents undergoing anterior cruciate ligament surgery. Am J Sports Med 43:282–288
16. Nwachukwu BU, McFeely ED, Nasreddine A, Udall JH, Finlayson C, Shearer DW, Micheli LJ, Kocher MS (2011) Arthrofibrosis and anterior cruciate ligament reconstruction in children and adolescents. J Pediatr Orthop 31:811–817
17. Shelbourne KD, Wilcken JH, Mollabashy A, DeCarlo M (1991) Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. Am J Sports Med 19:332–336
18. Smith TO, Davies L, Hing CB (2010) Early versus delayed surgery for anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc 18:304–311
19. Wasilewski SA, Covall DJ, Cohen S (1993) Effect of surgical timing on recovery and associated injuries after anterior cruciate ligament reconstruction. Am J Sports Med 21:338–342

4

Early Versus Delayed ACL Reconstruction: Why Delayed Surgery Is Our Preferred Choice

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4.1 Introduction

The senior authors believe that every knee injury is different, and their treatment needs to be considered on an individual basis taking many factors into account. In a small subset of cases with an isolated ACL tear and minimal swelling, good quadriceps control, and range of motion, early ACL reconstruction can be done safely. In our experience, the majority of cases can be done electively. The exception being when there is a concomitant fracture or significant posterolateral corner injury that should be done more urgently. Delaying in this setting can make the surgical treatment much more difficult and with potentially worse outcomes. We feel this outweighs the risk of arthrofibrosis. Excluding these semi-urgent cases, immediately performing an elective ACL reconstruction can place the patient at a higher risk for significant complications with little additional benefit.

The purpose of this chapter is to present the advantages and disadvantages of delayed and late ACL reconstruction. We will begin by defining the terms "early," "delayed," and "late" as there is no consensus on these definitions in orthopedic literature. We will also define the types and phases of ACL injuries for purposes of this chapter. We will then discuss evidence as it relates to our preferred approach for delaying ACL reconstruction in the acutely injured knee. If early surgery is elected (or even in the delayed setting) and arthrofibrosis occurs, the surgeon should be well prepared to manage this complication, and we then provide recommendations for the treatment of arthrofibrosis. We will conclude with a review of the literature on nonoperative management of ACL injuries with the option for late reconstruction.

4.2 Definitions

There is no consensus definition for early, delayed, and late ACL reconstruction. A recent systematic review on the topic identified 22 articles comparing the results of early and delayed ACL reconstruction [1]. They found that early ACL reconstruction was defined in the studies they reviewed as ranging anywhere from 2 days

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Table 4.1 Definition of ACL injury types and reconstruction timing

Timing of ACL injury	Definition
Acute	<3 weeks from injury
Semi-acute	3–8 weeks from injury
Chronic	>8 weeks from injury
Other factors	
Isolated	No other ligamentous injury
Combined	Concomitant injury to MCL, PCL, or PLC
Timing of ACL reconstruction	
Early	Prior to resolution of inflammation and effusion, incomplete range of motion, and quad control
Delayed	After resolution of inflammation and effusion, full range of motion, and quad control
Late	After trial of nonoperative management

to 7 months post-injury, whereas delayed reconstruction was considered as anywhere from 3 weeks to 24 years post-injury. For the purpose of this chapter, we will use the following consistent definitions for sake of clarity. When a patient tears their ACL, they enter an acute injury phase, which typically lasts 3 weeks from their injury. They remain in a semi-acute phase until approximately 8 weeks when they enter the chronic phase of injury. However, when referring to ACL reconstruction timing, we will define early versus delayed versus late based upon the patient's clinical presentation (Table 4.1).

The early and delayed phases for ACL reconstruction are based more upon patient evaluation than any defined time period. The early phase consists of a swollen knee with a large effusion, poor quadriceps control, decreased range of motion, and an antalgic gait. The delayed phase marks the end of the early phase when a patient is able to ambulate with a normal gait and demonstrate a full active range of motion and good function of the extensor mechanism. Based upon the particular injury pattern, patient physiology, and rehabilitation, the early phase may last anywhere from a few days to a few months, with the typical patient entering the delayed phase within a couple of weeks. Separately, we define the concept of a late reconstruction as one that occurs with persistent instability after a failure of nonoperative management. Of course, the main issue here is recurrent reinjuries and further meniscus and articular cartilage damage (often irreversible).

4.3 Delayed ACL Reconstruction: Our Approach to the Acutely Injured Knee

Our initial approach to the acutely injured knee involves a careful history, physical examination involving assessment of all ligaments, and well-done x-rays. An MRI in this setting can be very helpful as physical examination due to the swelling and pain is often unreliable. After obtaining the above studies, the specific diagnosis can be made, and operative versus nonoperative treatment can be decided upon. It is our preference for the acutely swollen knee with poor motion and poor quad control that doesn't have any collateral ligament injury to enter into rehabilitation until normal motion and gait are restored.

There are certain circumstances in which early surgery may be preferable to delayed ACL reconstruction. If the ACL tear occurs in conjunction with a tibial or femoral fracture requiring reduction and fixation, the fracture care will supersede in importance and should be performed when the soft tissue envelope allows. In a multiligamentous knee injury with an unstable posterolateral corner, early repair or reconstruction of the posterolateral corner, regardless of ACL reconstruction timing, yields good results and potentially better outcomes than delayed surgery [18, 35]. There are two scenarios where an early ACL reconstruction may be of benefit. In the setting of a locked and irreducible meniscal tear, early surgery to reduce and treat the meniscus in conjunction with ACL reconstruction offers earlier motion without chondral damage and likely a better chance to repair the meniscus. Though there is limited evidence to support this, the final scenario is that of the high-level, typically professional, athlete whereby delaying surgery and return to play by a few weeks could potentially have a significant impact, financial and otherwise, upon their lives.

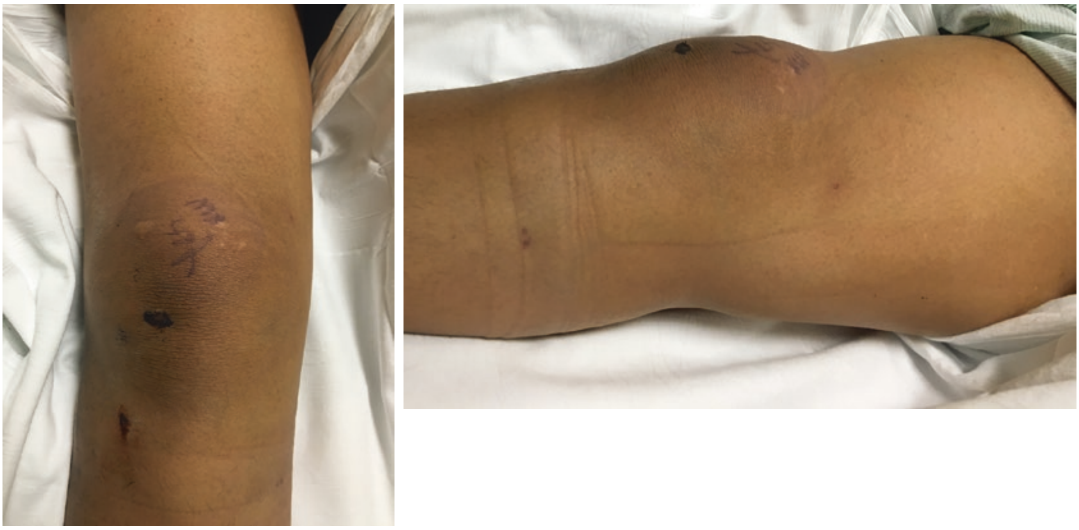

Fig. 4.1 Photograph of an acutely injured knee (ACL and MCL 5 days out – rephrase) demonstrating an effusion and ecchymosis

In the majority of the cases, a patient presents with an acutely swollen knee (Fig. 4.1), limited range of motion, and poor control of the quadriceps. In these cases and in the case of the multiligament-injured knee, in the absence of an operative posterolateral corner injury, early surgery is likely to lead to an increased risk of arthrofibrosis [31]. These patients are referred for rehabilitation until they enter the delayed phase with good quadriceps control and a complete active range of motion.

Multiple studies have reported the correlation between timing of ACL surgery and the risk of postoperative stiffness. Harner et al. initially described surgery within a month of injury as a risk factor for postoperative stiffness [13]. In a classic study, Shelbourne found that ACL reconstruction with bone-tendon-bone autograft delayed by more than 3 weeks post-injury resulted in a decreased incidence of arthrofibrosis and lack of full extension [34]. In a later review, Shelbourne listed the advantages of delayed reconstruction as obtaining a full range of motion without knee stiffness and a faster and safer return to full activities, noting that a functional yet lax knee is preferable to a stiff, stable knee [31, 32]. Passler et al. evaluated the complications following bone-tendon-bone ACL reconstruction in a group of 283 patients performed via a mini-arthrotomy. They reported that 18 % of patients who had surgery within a week after injury suffered arthrofibrosis as compared with only 6 % who had reconstruction delayed by more than 4 weeks [26]. Finally, Mauro et al. identified preoperative failure to gain full extension and a shorter interval between injury and surgery as risk factors for postoperative loss of extension [22].

On the other hand, good results have been shown with early reconstruction with bone-tendon-bone autografts [21]. In a prospective study, Hunter et al. reported results of 185 ACL reconstructions done in four different time intervals after injury [14]. In this study, authors divided patients into four groups according to reconstruction times: the first group had immediate surgery within the 48 h, the second group in 1 week, the third group in 3 weeks, and the fourth group after 3 weeks. One hundred forty-eight ACL reconstructions were done within 3 weeks, and only 11 had postoperative complications, which did not reach statistical significance. In these studies, reconstructions were done with bone-tendon-bone autografts, which is reported as an independent risk factor for knee stiffness in adolescents [25].

There is also conflicting data regarding the outcomes of ACL reconstructions performed with hamstring autografts with regard to surgical timing. In the 1990s, Wasilewski et al. reported arthrofibrosis in 22 % of acute reconstructions in a group of 87 ACL reconstructions with hamstring autografts [36]. In the 2000s, Meighan et al. reported an increased rate of complications such as stiffness and deep vein thromboses in the early group (within 2 weeks of injury) as compared with the delayed group (8–12 weeks) in a prospective randomized trial of 31 hamstring autograft ACL reconstructions [24]. However, in another prospective randomized study in 2008, Bottoni et al. performed 34 hamstring autograft ACL reconstructions in the early group at a mean time of 9 days after injury (the earliest surgery was done on the second day), and there was no significant difference between early versus delayed reconstruction group [4]. In 2010, Raviraj et al. randomized 105 patients with an isolated (no concomitant meniscal repair or other ligamentous injury) ACL tear to early (<2 weeks) or delayed (4–6 weeks) ACL reconstruction, and they found no difference in Lysholm or Tegner scores and no difference in range of motion [28].

There is now recent evidence across graft types to suggest that the timing of surgery may not increase the risk of postoperative stiffness for the isolated ACL tear. A recent meta-analysis of eight studies, including three randomized controlled trials, found no difference in adverse outcomes with ACL reconstruction performed at 1, 2, 10, 12, or 20 weeks after injury when performed with a modern reconstruction technique and accelerated rehab protocol [16].

In the experience of the senior authors, the clinical status of the injured knee at time of surgery, not the timing of the injury, is the most important factor. Mayr et al. did not assess the timing of ACL reconstruction, but they assessed preoperative symptoms such as swelling, effusion, and extension or flexion deficits at the time of surgery. They found that failure to regain a full range of motion preoperatively was a risk factor for postoperative stiffness regardless of timing of surgery [23].

ACL reconstruction is an elective procedure, and because of the risk of postoperative stiffness and loss of extension, we routinely wait until a patient has entered the delayed phase. As we previously noted, the delayed phase is patient dependent and may last anywhere from a few days to occasionally a few months. During the time, it is imperative that the patient be actively involved in rehabilitation to assist them in their transition from the early to the delayed phase. Further, the extra time allows the patient to schedule their surgery around their other obligations (social, work, school, family, etc.).

Text Box 4.1 Advantages and Disadvantages of Delayed ACL Reconstruction

Advantages	Decreased risk of postoperative stiffness and loss of motion
	Allows for patient/family to plan around other obligations (social, family, work, school, etc.)
Disadvantages	Potential delayed return to play by a few weeks
	May preclude treatment of a locked, irreducible meniscal tear
	In acute combined ligament injured knee, delay may worsen outcome of posterolateral corner injury

4.4 Diagnosis and Treatment of Arthrofibrosis

Arthrofibrosis is a known and frustrating complication of ACL tears and reconstructions for both patient and surgeon. Development of postoperative arthrofibrosis and stiffness following elective or urgent ACL reconstruction is a time-consuming and debilitating problem, especially in athletes. It can be seen on MRI as disorganized scar tissue anterior to the ACL (Fig. 4.2). Though arthrofibrosis has been classified into four subtypes with the most mild form being less than a 10° extension loss and normal flexion, a loss of motion of 3–5° in an athlete can lead to significant disability including quadriceps inhibition and a permanent decrease in performance. Further, the treatment of arthrofibrosis, even when successful, can delay return

Fig. 4.2 MRI of a knee demonstrating arthrofibrosis. There is excess disorganized scar tissue anterior to the reconstructed ACL involving the fat pad

to play, potentially negating any benefits from an early ACL reconstruction [33].

Unfortunately, arthrofibrosis remains a common problem today after ACL reconstructions. A 2015 epidemiologic study on arthrofibrosis after ACL reconstruction found that 1.7 % of patients that underwent ACL reconstruction had postoperative stiffness requiring procedural intervention, and a separate study in 902 pediatric and adolescent patients that had undergone ACL reconstruction required procedural intervention for arthrofibrosis in 8.3 % of patients [25, 30].

Certain patients are likely more prone to forming scar and to developing arthrofibrosis than others, and it is important for the physician to recognize this. In the experience of the senior authors, patients with complex regional pain syndrome or a poor pain tolerance may develop a stiff and painful knee 1–2 months out from their injury despite adequate attempts at rehabilitation. In this particular patient group, we strongly recommend against early ACL reconstructions, and, even in delayed reconstructions, close attention needs to be paid to their motion postoperatively.

We prefer the delayed surgical approach so that we can treat these patients and their potential stiffness prior to ACL reconstruction, which may prevent a disastrous postoperative stiffness; however, it is important to know how to treat this complication regardless of whether it is preoperative or postoperative. When these patients are 4–6 weeks out from their injury or surgery, we consider a loss of extension of greater than 3° a significant complication, and if it doesn't rapidly improve, then we consider further treatment. Multiple authors including Paulos et al., Fisher et al., and Shelbourne et al. reported good return of motion and function after manipulation under anesthesia, arthroscopic excision of anterior scar tissue, the optional use of a drop-out cast, and aggressive rehabilitation with sparing use of medial and lateral capsular releases [9, 27, 33].

4.5 Late ACL Reconstruction

Late ACL reconstructions in chronically ACL deficient knees may be due to either to a missed diagnosis or due to an initial trial of nonoperative management. It is critical to point out that nonoperative treatment does not mean no treatment. Well-instructed physical therapy is a necessary component of treatment and can lead to nearly similar outcomes as ACL reconstruction in some individuals [10, 11]. One of the critical components of nonoperative management is also counseling to avoid certain activities that may lead to further injury. The senior authors also recommend a brace for certain activities. If instability remains an issue, then surgical treatment is recommended.

In adults over the age of 40, in particular if the patient is less active or already has radiographic evidence of osteoarthritis, nonoperative management may either have a higher chance of success or a lower risk of worsening the preceding osteoarthritis. ACL reconstructions in the over 40 population have shown good results consistent with that of younger adults, but less is known about any potential risk for delaying surgery as a late reconstruction [5, 7, 20]. The other population where late reconstruction has been proposed is in skeletally immature patients whereby late surgery can allow for closure of or less risk of damage to the physes with reconstruction [17, 37]. However, there is currently a trend away from prolonged nonoperative management in these patients as Dumont et al. recently found a higher rate of medial meniscal tears in pediatric patients greater than 150 days from their injury [8].

The concern for subsequent injuries to cartilage and menisci with prolonged nonoperative management exists in the young active adult population as well. Anstey et al. found 16.7 % of patients that had surgery greater than 6 months out from their ACL injury had new medial meniscal tears as compared with only 4.1 % of those with earlier surgery ($p = 0.01$), and Magnussen et al. noted 39.6 % of patients with medial meniscal tears and 37.4 % with medial chondral injuries with reconstruction performed greater than 12 weeks after their injury as compared with 24.8 % and 16.7 % with earlier surgery ($p = 0.013$ and $p < 0.005$, respectively) [2, 19]. Multiple other studies have found similar results, and Krutsch et al. found that surgery greater than 6 months from the injury decreases the likelihood of a meniscal tear being reparable from 77.2 % to 46.7 % ($p = 0.022$) [6, 12, 15, 38].

In Sweden, Frobell et al. randomized 121 young active adults with ACL tears to rehabilitation with "early" (less than 10 weeks) ACL reconstruction versus rehabilitation with optional "delayed" (average of 11.6 months after randomization) ACL reconstruction. A total of 23 of 59 of the optional "delayed" group had persistent symptoms and underwent surgery. At 2 years and at 5 years, there was no difference between the two groups in terms of the KOOS score, SF-36, or their Tegner activity scale [10, 11].

The effectiveness of treating all young active adults with ACL injuries with an initial course of nonoperative management has been studied since the above trial. J Bernstein performed a decision analysis that takes into account the potential sequelae of untreated meniscal tears and determined that early surgery is most effective as long as the costs of a potential meniscal tear are more than 5.25 times that of an ACL reconstruction [3]. One systematic review found that of the three economic cost utility analyses, ACL reconstruction is more cost-effective than nonoperative management with rehabilitation alone [29]. Though there is no definitive answer to whether nonoperative management should be considered as a primary treatment, the majority of Level II and III studies suggest that late ACL reconstruction is more costly and potentially exposes the patient to a higher risk of meniscal and chondral injury.

References

1. Andernord D, Karlsson J, Musahl V, Bhandari M, Fu FH, Samuelsson K (2013) Timing of surgery of the anterior cruciate ligament. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(11):1863–1871
2. Anstey DE, Heyworth BE, Price MD, Gill TJ (2012) Effect of timing of ACL reconstruction in surgery and development of meniscal and chondral lesions. Phys Sportsmed 40(1):36–40
3. Bernstein J (2011) Early versus delayed reconstruction of the anterior cruciate ligament: a decision analysis approach. J Bone Joint Surg Am 93(9):e48
4. Bottoni CR, Liddell TR, Trainor TJ, Freccero DM, Lindell KK (2008) Postoperative range of motion following anterior cruciate ligament reconstruction using autograft hamstrings: a prospective, randomized clinical trial of early versus delayed reconstructions. Am J Sports Med 36(4):656–662
5. Brown CA, McAdams TR, Harris AH, Maffulli N, Safran MR (2013) ACL reconstruction in patients aged 40 years and older: a systematic review and introduction of a new methodology score for ACL studies. Am J Sports Med 41(9):2181–2190
6. Demirag B, Aydemir F, Danis M, Ermutlu C (2011) Incidence of meniscal and osteochondral lesions in patients undergoing delayed anterior cruciate ligament reconstruction. Acta Orthop Traumatol Turc 45(5):348–352
7. Desai N, Bjornsson H, Samuelsson K, Karlsson J, Forssblad M (2014) Outcomes after ACL reconstruction with focus on older patients: results from The Swedish National Anterior Cruciate Ligament Register. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 22(2):379–386
8. Dumont GD, Hogue GD, Padalecki JR, Okoro N, Wilson PL (2012) Meniscal and chondral injuries associated with pediatric anterior cruciate ligament tears: relationship of treatment time and patient-specific factors. Am J Sports Med 40(9):2128–2133
9. Fisher SE, Shelbourne KD (1993) Arthroscopic treatment of symptomatic extension block complicating anterior cruciate ligament reconstruction. Am J Sports Med 21(4):558–564
10. Frobell RB, Roos EM, Roos HP, Ranstam J, Lohmander LS (2010) A randomized trial of treatment for acute anterior cruciate ligament tears. N Engl J Med 363(4):331–342
11. Frobell RB, Roos HP, Roos EM, Roemer FW, Ranstam J, Lohmander LS (2013) Treatment for acute anterior cruciate ligament tear: five year outcome of randomised trial. BMJ 346:f232

12. Ghodadra N, Mall NA, Karas V et al (2013) Articular and meniscal pathology associated with primary anterior cruciate ligament reconstruction. J Knee Surg 26(3):185–193
13. Harner CD, Irrgang JJ, Paul J, Dearwater S, Fu FH (1992) Loss of motion after anterior cruciate ligament reconstruction. Am J Sports Med 20(5):499–506
14. Hunter RE, Mastrangelo J, Freeman JR, Purnell ML, Jones RH (1996) The impact of surgical timing on postoperative motion and stability following anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 12(6):667–674
15. Krutsch W, Zellner J, Baumann F, Pfeifer C, Nerlich M, Angele P (2015) Timing of anterior cruciate ligament reconstruction within the first year after trauma and its influence on treatment of cartilage and meniscus pathology. Knee Surg Sports Traumatol Arthrosc [Epub ahead of print].
16. Kwok CS, Harrison T, Servant C (2013) The optimal timing for anterior cruciate ligament reconstruction with respect to the risk of postoperative stiffness. Arthroscopy 29(3):556–565
17. Larsen MW, Garrett WE Jr, Delee JC, Moorman CT 3rd (2006) Surgical management of anterior cruciate ligament injuries in patients with open physes. J Am Acad Orthop Surg 14(13):736–744
18. Levy BA, Dajani KA, Whelan DB et al (2009) Decision making in the multiligament-injured knee: an evidence-based systematic review. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 25(4):430–438
19. Magnussen RA, Pedroza AD, Donaldson CT, Flanigan DC, Kaeding CC (2013) Time from ACL injury to reconstruction and the prevalence of additional intra-articular pathology: is patient age an important factor? Knee Surg Sports Traumatol Arthrosc 21(9):2029–2034
20. Mall NA, Frank RM, Saltzman BM, Cole BJ, Bach BR Jr (2015) Results after anterior cruciate ligament reconstruction in patients older than 40 years: how do they compare with younger patients? A systematic review and comparison with younger populations. Sports Health 8(2):177–181.
21. Marcacci M, Zaffagnini S, Iacono F, Neri MP, Petitto A (1995) Early versus late reconstruction for anterior cruciate ligament rupture. Results after five years of followup. Am J Sports Med 23(6):690–693
22. Mauro CS, Irrgang JJ, Williams BA, Harner CD (2008) Loss of extension following anterior cruciate ligament reconstruction: analysis of incidence and etiology using IKDC criteria. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 24(2):146–153
23. Mayr HO, Weig TG, Plitz W (2004) Arthrofibrosis following ACL reconstruction – reasons and outcome. Arch Orthop Trauma Surg 124(8):518–522
24. Meighan AA, Keating JF, Will E (2003) Outcome after reconstruction of the anterior cruciate ligament in athletic patients. A comparison of early versus delayed surgery. J Bone Joint Surg Br Vol 85(4):521–524
25. Nwachukwu BU, McFeely ED, Nasreddine A et al (2011) Arthrofibrosis after anterior cruciate ligament reconstruction in children and adolescents. J Pediatr Orthop 31(8):811–817
26. Passler JM, Schippinger G, Schweighofer F, Fellinger M, Seibert FJ (1995) Complications in 283 cruciate ligament replacement operations with free patellar tendon transplantation. Modification by surgical technique and surgery timing. Unfallchirurgie 21(5):240–246
27. Paulos LE, Rosenberg TD, Drawbert J, Manning J, Abbott P (1987) Infrapatellar contracture syndrome. An unrecognized cause of knee stiffness with patella entrapment and patella infera. Am J Sports Med 15(4):331–341
28. Raviraj A, Anand A, Kodikal G, Chandrashekar M, Pai S (2010) A comparison of early and delayed arthroscopically-assisted reconstruction of the anterior cruciate ligament using hamstring autograft. J Bone Joint Surg Br Vol 92(4):521–526
29. Saltzman BM, Cvetanovich GL, Nwachukwu BU, Mall NA, Bush-Joseph CA, Bach BR Jr (2015) Economic analyses in anterior cruciate ligament reconstruction: a qualitative and systematic review. Am J Sports Med
30. Sanders TL, Kremers HM, Bryan AJ, Kremers WK, Stuart MJ, Krych AJ (2015) Procedural intervention for arthrofibrosis after ACL reconstruction: trends over two decades. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA
31. Shelbourne KD, Carr DR (2003) Combined anterior and posterior cruciate and medial collateral ligament injury: nonsurgical and delayed surgical treatment. Instr Course Lect 52:413–418
32. Shelbourne KD, Patel DV (1995) Timing of surgery in anterior cruciate ligament-injured knees. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 3(3):148–156
33. Shelbourne KD, Patel DV, Martini DJ (1996) Classification and management of arthrofibrosis of the knee after anterior cruciate ligament reconstruction. Am J Sports Med 24(6):857–862
34. Shelbourne KD, Wilckens JH, Mollabashy A, DeCarlo M (1991) Arthrofibrosis in acute anterior cruciate ligament reconstruction. The effect of timing of reconstruction and rehabilitation. Am J Sports Med 19(4):332–336
35. Subbiah M, Pandey V, Rao SK, Rao S (2011) Staged arthroscopic reconstructive surgery for multiple ligament injuries of the knee. J Orthop Surg 19(3):297–302
36. Wasilewski SA, Covall DJ, Cohen S (1993) Effect of surgical timing on recovery and associated injuries after anterior cruciate ligament reconstruction. Am J Sports Med 21(3):338–342
37. Woods GW, O'Connor DP (2004) Delayed anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med 32(1):201–210
38. Yoo JC, Ahn JH, Lee SH, Yoon YC (2009) Increasing incidence of medial meniscal tears in nonoperatively treated anterior cruciate ligament insufficiency patients documented by serial magnetic resonance imaging studies. Am J Sports Med 37(8):1478–1483

5 Diagnostic Accuracy of Physical Examinations for ACL Injury

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5.1 Introduction

Physical examination is an important aspect of the initial diagnosis and decision-making process, particularly in musculoskeletal injuries such as a rupture of the anterior cruciate ligament (ACL). It is critical that physicians are aware of the evidence available concerning the diagnostic accuracy of the physical examination maneuvers in order to form a proper diagnosis and provide proper and prompt management.

The accuracy of the physical examination is usually assessed by evaluating how often a positive or negative result accurately correlates with the presence or absence of a given condition. *Sensitivity* refers to the percentage of patients with the condition who have a positive test result, while *specificity* refers to the percentage of patients without the condition who have received a negative test result (Fig. 5.1). On the other hand, the positive predictive value refers to the percentage of patients with a positive test result who actually have the condition, while the negative predictive value refers to the percentage of patients who tested negative and who truly do not have the condition. While the positive and negative predictive values appear to be of more use when evaluating a diagnostic tool due to their ease of applicability in a clinical setting, these values are actually much less reliable as they are highly dependent on the prevalence of the condition in the study population. The sensitivity and specificity of the various tests, as reported in literature, will therefore be conveyed throughout this entry rather than the positive and negative predictive values as they can be applied to any population. In general, a test with a high sensitivity has few false-negative results indicating it is a useful test for exclusion with a negative test result. A test with a high specificity would have few false-positive results indicating that such a test is useful for diagnosis when the test result is positive. In practice, however, sensitivities and specificities do not precisely indicate the quantitative change in probability of the condition after a test result. *Positive* and *negative likelihood ratios* (LR+, LR−) are used in order to quantify the shift in probability of the condition. The larger the LR+ (calculated as the sensitivity

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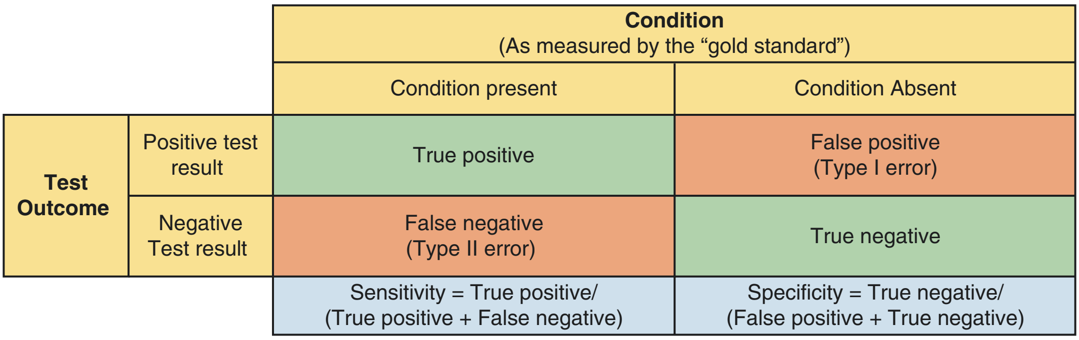

		Condition (As measured by the "gold standard")	
		Condition present	Condition Absent
Test Outcome	Positive test result	True positive	False positive (Type I error)
	Negative Test result	False negative (Type II error)	True negative
		Sensitivity = True positive/ (True positive + False negative)	Specificity = True negative/ (False positive + True negative)

Fig. 5.1 Representation of the calculation of the sensitivity and specificity of a diagnostic test

divided by one minus the specificity) and the smaller the LR− (calculated as one minus the sensitivity divided by the specificity), the higher the change in odds favoring the condition [12].

The three most common physical examinations that test for ACL insufficiency are the anterior drawer test, Lachman's test, and the pivot shift test. Before the 1970s, the only physical examination that was used for diagnosis was the anterior drawer test. The exact origins of the anterior drawer test remains uncertain, and descriptions of similar tests have been identified in published work dating back to 1875 [14]. The first published description of Lachman's test was provided by Torg et al. in 1976 [16], although descriptions of similar tests have been found in earlier publications [11]. The pivot shift test was described initially by Galway in 1972 and was introduced into routine clinical examinations in the 1980s [4].

This chapter describes these three physical examination maneuvers that are used to assess ACL instability and present the evidence that is available regarding their diagnostic accuracy and reliability.

5.2 Anterior Drawer Test

5.2.1 Test Description

The examination is performed with the patient in supine position with the hip at 45° flexion and the knee at 90° flexion. The lower leg is held in neutral rotation with the examiner using either their thigh to stabilize the patient's forefoot or forearm to stabilize the patient's shin. The examiner then places the fingers of both of their hands in the popliteal fossa with the thumbs over the tibial plateau and anterior joint line. A slow, but firm, anteriorly directed force is then applied to the proximal tibia. A positive test result is an increased anterior tibial translation of the involved leg in comparison to the uninvolved leg, and this is indicative of an ACL tear.

5.2.2 Strengths and Limitations

The anterior drawer test has the benefit of being the least challenging test to perform; however, there are several limitations to the test that may lead to inaccurate diagnoses. The first flaw arises from the occasional difficultly placing the knee at 90° flexion due to muscle guarding and effusion that often accompany ACL injuries. Furthermore, when at 90° flexion the hamstring muscles may act to stabilize the tibia, preventing anterior translation. Lastly, the anatomy of the knee joint when flexed at 90° is such that the convex surface of the posterior femoral condyle and the concave surface of the medial tibia plateau and posterior horn of the medial meniscus may interact in a manner similar to a "door stopper" which impedes anterior translation. Each of these potential flaws, due to the nature of the examination placing the knee at 90° flexion, could increase the likelihood of a false-negative result when performing the anterior drawer test [14]. False-positive results with the anterior drawer test may arise from PCL

Table 5.1 Summary of the pooled sensitivities and specificities reported for the anterior drawer test performed in various circumstances

Test condition	Source	No. of subjects	Sensitivity [% (95 % CI)]	Specificity [% (95 % CI)]
General	Scholten (2003)	1,061	62 (42–78)	88 (83–92)
	Benjaminse (2006)	1,809	55 (52–58)	92 (90–94)
Acute ACL injury	Benjaminse (2006)	298	49 (43–45)	
Chronic ACL injury	Benjaminse (2006)	531	92 (88–95)	
With anesthesia	Benjaminse (2006)	1,306	77 (75–80)	87 (82–91)
	van Eck (2013)	934	63	91
Without anesthesia (acute, complete ruptures)	van Eck (2013)	826	38	81

Table 5.2 Summary of the pooled sensitivities and specificities reported for Lachman's test performed in various circumstances

Test condition	Source	No. of subjects	Sensitivity [% (95 % CI)]	Specificity [% (95 % CI)]
General	Scholten (2003)	969	86 (76–92)	91 (79–96)
	Benjaminse (2006)	2,276	85 (83–87)	94 (92–95)
	Leblanc (2015)	990	89 (76–98)	
Acute ACL injury	Benjaminse (2006)	298	94 (91–96)	
Chronic ACL injury	Benjaminse (2006)	531	95 (91–97)	
Partial ACL rupture	Leblanc (2015)	243	68 (25–98)	
Complete ACL rupture	Leblanc (2015)	618	96 (90–100)	
With anesthesia	van Eck (2013)	934	91	78
Without anesthesia (acute, complete ruptures)	van Eck (2013)	826	81	81
Prone position	Mulligan (2011)	52	70 (49–84)	97 (83–99)

injuries where the sagging tibia is taken as the normal position of the proximal tibia causing a movement to normal position to appear as an anterior translation [9]. In order to avoid such errors, it is important to consider the "step-off" which is the shortest distance from the femur to a hypothetical line extending tangentially from the tibial tuberosity. A "step-off" less than 5 mm is indicative of a PCL injury, and any anterior movement from this position is not considered a positive anterior drawer test [8].

5.2.3 Accuracy

One meta-analysis of eight studies ($n = 1{,}061$) reported a pooled sensitivity of 62 % (95 % confidence interval [CI], 42–78 %) [13]. A second meta-analysis of 20 studies published before the year 2000 (including 7 of the 8 studies from the previous meta-analysis) with a total sample size of 1,809 patients reported a pooled sensitivity of 55 % (95 % CI, 52–58 %) [1] (Table 5.1). The former review also calculated a pooled specificity of 88 % (95 % CI, 83–92 %) based on a meta-analysis of seven studies ($n = 929$) [13] (Table 5.2). The latter review performed a meta-analysis of 12 studies (half of which were included in the previous meta-analysis analysis) with a total sample size of 1,420 patients and reported a pooled specificity of 92 % (95 % CI, 90–94 %), for a pooled positive likelihood ratio (LR+) of 7.3 (95 % CI, 3.5–15.2) and a pooled negative likelihood ratio (LR−) of 0.5 (95 % CI, 0.4–0.6) [1]. Another systematic review reported variable LR+ and LR− with ranges of 2.0–87.9 and 0.23–0.74, respectively; however, the authors of the review

Table 5.3 Summary of the pooled sensitivities and specificities reported for the pivot shift test performed in various circumstances

Test condition	Source	No. of subjects	Sensitivity [% (95 % CI)]	Specificity [% (95 % CI)]
General	Benjaminse (2006)	1,431	24 (21–27)	98 (96–99)
	Leblanc (2015)	948	79 (63–91)	
Partial ACL rupture	Leblanc (2015)	227	67 (47–83)	
Complete ACL rupture	Leblanc (2015)	586	86 (68–99)	
With anesthesia	Benjaminse (2006)	1,077	74 (71–77)	98
	van Eck (2013)	1,192	73	
Without anesthesia (acute, complete ruptures)	van Eck (2013)	826	28	81

did not calculate pooled values because of the substantial heterogeneity of the data, wide confidence intervals in the reported values, and concerns of high bias risk in five of the six studies included in the review [15].

5.2.3.1 Type of Injury

When the studies were distinguished by chronicity of the injury, the pooled sensitivity of the maneuver performed on acute injuries was 49 % (95 % CI, 43–55 %) based on a total sample size of 298 patients. The sensitivity of the anterior drawer performed on chronic injuries was much higher, namely, 92 % (95 % CI, 88–95 %) based on an aggregate of 531 patients [1]. It is thought that patients with ACL insufficiency over a long period of time have developed chronic knee laxity, which is expected to improve the accuracy of the test due to fewer false-negative results from muscle guarding.

5.2.3.2 Effect of Anesthesia

Under anesthesia, muscle guarding is no longer a factor; thus the sensitivity of the anterior drawer test is expected to increase due to fewer false-negative results. The pooled sensitivity of the test with anesthesia was calculated to be 77 % (95 % CI, 75–80 %) by a meta-analysis of 15 studies published before the year 2000 ($n = 1{,}306$). The pooled specificity, LR+, and LR− were calculated to be 87 % (95 % CI, 82–91 %), 5.9 (95 % CI, 0.9–38.2), and 0.4 (95 % CI, 0.2–0.8), respectively, by a meta-analysis of seven studies with a total sample size of 713 patients [1]. The ACL injuries were not differentiated by chronicity or type (partial or complete) in this systematic review. Another meta-analysis of 14 studies (with 11 of these included in the previous meta-analysis) reported a pooled sensitivity of acute, complete ruptures under anesthesia of 63 % ($n = 934$) compared to 38 % without anesthesia ($n = 826$) [17] (Tables 5.3, 5.4, and 5.5).

Anterior Drawer Test

- Low sensitivity and limited use in excluding ACL insufficiency with a negative test result in acute injuries.
- Much higher sensitivity in chronic injuries.
- Moderate specificity, although lower than specificity in Lachman's and pivot shift tests.

5.3 Lachman's Test

5.3.1 Test Description

The examination is performed with the examiner on the side of the injured leg and the patient in supine position. The femur is stabilized in one hand with the knee at slight flexion (between 0° and 15°). The other hand is used in an attempt to translate the proximal aspect of the tibia anteriorly by applying a brisk force to the posterior aspect. If the ACL is intact, one does not expect much anterior translation of the tibia, and the

Table 5.4 Sensitivity [% (95 % CI)] of the anterior drawer, Lachman, and pivot shift tests performed on awake patients as reported by available evidence

Source	Design	No. of subjects	Anterior drawer	Lachman	Pivot shift
Boeree (1991)[a]	Prospective	203	56 (42–69)	63 (49–75)	31 (19–44)
Cooperman (1990)[a]	Prospective	32		71 (40–92)	
Hardaker (1990)[a]	Unclear	132	18 (11–27)	74 (65–82)	29 (20–39)
Lee (1988)[a]	Prospective	79	78 (56–93)	91 (72–99)	
Richter (1996)	Prospective	74	67 (54–79)	93 (83–98)	48 (35–62)
Rubinstein (1994)[a]	Prospective	39	76 (38–96)	96 (60–100)	93 (57–100)
Sandberg (1986)[a]	Retrospective	182	39 (30–48)	48 (39–57)	6 (2–11)
Schwartz (1997)[a]	Prospective	58		92 (80–98)	
Steinbrück (1988)[a]	Unclear	300	92 (81–98)	86 (74–94)	22 (11–35)
Tonino (1986)[a]	Prospective	52	27 (12–46)	90 (74–98)	17 (6–35)
Scholten (2003) meta-analysis[b]			**62 (42–78)**	**86 (76–92)**	–
Anderson (1989)	Prospective	50	27 (14–43)	91 (79–98)	42 (27–58)
Bomberg (1990)	Prospective	32	41 (21–64)	86 (65–97)	9 (1–29)
Braunstein (1982)	Prospective	29	91 (59–100)		
Dahlstedt (1989)	Prospective	41		100 (85–100)	9 (1–28)
				100 (85–100)	72 (47–90)
DeHaven (1980)	Prospective	113	9 (2–23)	80 (52–96)	9 (2–23)
Donaldson (1985)	Retrospective	37	70 (60–79)	99 (95–100)	35 (26–45)
Harilainen (1987)	Prospective	350		98 (94–100)	
Hughston (1976)	Prospective	68	58 (37–78)		
Jonsson (1982)	Prospective	107	95 (87–99)	97 (89–100)	
Learmonth (1991)	Prospective	62		68 (55–79)	
Liu (1995)	Retrospective	38	61 (43–76)	95 (82–99)	71 (54–85)
Mitsou (1988)	Retrospective	144	40 (28–54)	99 (94–100)	
			95 (88–99)		
Noyes (1980)	Prospective	85	25 (15–37)		
Otter (1994)	Prospective	58			0 (0–71)
Torg (1976)	Retrospective	250	52 (44–61)	96 (92–99)	9 (5–15)
Warren (1978)	Retrospective	136	71 (61–80)		
Benjaminse (2006) meta-analysis[b]			**55 (52–58)**	**85 (83–87)**	**24 (21–27)**
Beldame (2011)	Prospective	112	70 (58–81)	81 (71–89)	60 (45–73)
Dejour (2013)	Prospective	300		100 (99–100)	89 (85–92)
Panisset (2008)	Prospective	418		89 (84–92)	93 (89–96)
Peeler (2010)	Retrospective	112		86 (77–92)	63 (51–74)
Tsai (2004)	Retrospective	48		81 (67–91)	
Leblanc (2015) meta-analysis[b]			–	**89 (76–98)**	**79 (63–91)**

[a] These studies were also included in the meta-analysis reported by Benjaminse (2006)

[b] Meta-analyses whose values are calculated pooled sensitivities from data directly above

endpoint of the movement should feel "hard." In contrast, a positive result for Lachman's test would be a noticeable anterior movement of the tibia with an endpoint described as "soft" or "mushy" [16].

5.3.2 Strengths and Limitations

Similar to the anterior drawer test, Lachman's test is also used to observe whether anterior translation of the tibia exists; however, as

Table 5.5 Specificity [% (95 % CI)] of the anterior drawer, Lachman, and pivot shift tests performed on awake patients as reported by available evidence

Source	Design	No. of subjects	Anterior drawer	Lachman	Pivot shift
Boeree (1991)[a]	Prospective	203	92 (86–96)	90 (84–95)	97 (92–99)
Cooperman (1990)[a]	Prospective	32		54 (30–77)	
Lee (1988)[a]	Prospective	79	100 (94–100)	100 (94–100)	
Richter (1996)		74	88 (62–98)	88 (62–98)	97 (79–100)
Rubinstein (1994)[a]	Prospective	39	87 (69–96)	100 (89–100)	89 (73–97)
Sandberg (1986)[a]	Retrospective	182	97 (88–100)	97 (88–100)	100 (94–100)
Schwartz (1997)[a]	Prospective	58		56 (25–85)	
Steinbrück (1988)[a]	Unclear	300	91 (87–94)	92 (88–95)	99 (97–100)
Tonino (1986)[a]	Prospective	52	100 (85–100)	100 (85–100)	100 (85–100)
Scholten (2003) meta-analysis[b]			**88 (83–92)**	**91 (79–96)**	–
Bomberg (1990)	Prospective	32	100 (48–100)	60 (15–95)	100 (48–100)
Braunstein (1982)	Prospective	29	100 (82–100)		
Harilainen (1987)	Prospective	350		98 (94–99)	
Hughston (1976)	Prospective	68	50 (30–70)		
Learmonth (1991)	Prospective	62		94 (89–97)	
Noyes (1980)	Prospective	85	96 (79–100)		
Otter (1994)	Prospective	58			82 (57–96)
Torg (1976)	Retrospective	250	100 (95–100)	100 (95–100)	100 (95–100)
Warren (1978)	Retrospective	136	77 (56–91)		
Benjaminse (2006) meta-analysis[b]			**92 (90–94)**	**94 (92–95)**	**98 (96–99)**
Beldame (2011)	Prospective	112	84 (66–95)	78 (60–91)	86 (65–97)

[a]These studies were also included in the meta-analysis reported by Benjaminse in 2006

[b]Meta-analyses whose values are calculated pooled sensitivities from data directly above

opposed to the anterior drawer test, the knee is not placed at 90° flexion. This positioning eliminates some of the limitations experienced with the anterior drawer test described previously. The major limitation of Lachman's test is the difficulty performing the examination maneuver properly by examiners with small hands or on patients with a large thigh girth. In such instances, modified versions of the original Lachman's test are used [3].

5.3.3 Accuracy

The pooled sensitivity of Lachman's test was reported to be 86 % (95 % CI, 76–92 %), 85 % (95 % CI, 83–87 %), and 89 % (95 % CI, 76–98 %) by three meta-analyses of nine ($n=969$), 21 ($n=2{,}276$) and five ($n=990$) studies, respectively. The first two reviews had eight studies in common and included only studies published before the year 2000, while all five reports included in the second review were published after the year 2000 [1, 7, 13] (Table 5.1). The pooled specificity of Lachman's test was reported to be 91 % (95 % CI, 79–96 %) and 94 % (95 % CI, 92–95 %) by meta-analyses of eight ($n=837$) and 12 ($n=1{,}729$) studies, respectively (seven common studies in these two analyses) [1, 13] (Table 5.2). Pooled LR− and LR+ were reported to be 10.2 (95 % CI, 4.6–22.7) and 0.2 (95 % CI, 0.1–0.3) by a meta-analysis of 12 studies with an aggregate sample size of 1,729 [1]. Another systematic review reported variable LR+ and LR− with ranges of 1.39–40.89 and 0.02–0.52, respectively; however, the authors of the review did not perform a meta-analysis due to the heterogeneity of the LRs, concerns of wide confidence intervals, and high risk of bias in seven of the nine studies included in the review [15].

5.3.3.1 Type of Injury

The sensitivities of the tests were reported to be similar in both acute and chronic ACL injuries by meta-analyses of seven and eight studies, respectively. Lachman's test performed on patients with acute and chronic injuries showed a pooled sensitivity of 94 % (95 % CI, 91–96 %) and 95 % (95 % CI, 91–97 %), respectively [1]. The type of ACL injury, on the other hand, had a large effect on the accuracy of Lachman's test. A meta-analysis of six studies published after the year 2000 reported a pooled sensitivity of 68 % (95 % CI, 25–98 %) for partial ACL ruptures and 96 % (95 % CI, 90–100 %) for complete ruptures [7].

5.3.3.2 Effect of Anesthesia

In acute, complete ACL ruptures without anesthesia, a pooled sensitivity of 81 % was calculated for Lachman's test by a meta-analysis of 17 studies ($n = 1{,}578$). When patients were under anesthesia, the pooled sensitivity was calculated as 91 % by a meta-analysis of 13 studies ($n = 934$). The specificity of Lachman's test in acute, complete ACL injuries, on the other hand, was calculated as 81 % without anesthesia and 78 % with anesthesia [17].

5.3.4 Reliability

With respect to reliability of Lachman's test, results from different studies are variable. One study reported moderate intra-rater reliability with Cohen's kappa (k) of 0.46. The interrater reliability was assessed using Cohen's kappa by four studies with results ranging from $k = 0.19$ to $k = 0.60$. A systematic review assessing the reliability of Lachman's test did not perform a meta-analysis using these studies as there was heterogeneity noted in the results, and some of the studies were of poor methodological quality [6].

5.3.5 Prone Lachman's Test

Due to the difficulties performing the examination discussed earlier, a modified Lachman's test has been proposed where the patient is placed in prone position which decreases the need to stabilize the proximal femur. One study ($n = 52$) has examined the accuracy of Lachman's test in prone position and reported LR+ and LR− of 3.50 (95 % CI, 0.58–21.2) and 0.38 (95 % CI, 0.13–1.06), respectively. Although the sample size was small, the reported reliability of Lachman's test in prone position was higher than the reported values in supine position in terms of interrater reliability ($k = 0.80$) [10].

Lachman's Test

- Has the highest sensitivity and most accurate test for ruling out ACL injury.
- High sensitivity for both acute and chronic injuries, low sensitivity for partial ACL ruptures.
- High specificity, accurate for diagnosing ACL injury with positive test result.
- One small study demonstrates promising results, in terms of specificity, for Lachman's test in prone position [10].

5.4 Pivot Shift Test

5.4.1 Test Description

While the pivot shift is a phenomenon that is often described by the patient as "collapsing at the knee," in the clinical setting the pivot shift test involves a maneuver that attempts to produce this sensation. The underlying mechanism for this phenomenon that results from ACL insufficiency is the anterior subluxation of the tibia when the knee approaches extension and a sudden reduction of this subluxation as the knee is flexed [4]. The anterior subluxation is due to both quadriceps contraction as well as increased axial loading on the lateral compartment due to a valgus force. Practically, this occurs during sudden changes of direction or unexpected stops. This phenomenon can be elicited in the clinical setting with the maneuver known as the pivot shift test.

It is important for the patient to keep the leg completely relaxed in order for the test to produce the proper results. The test involves the examiner lifting the ankle of the patient with one hand and flexing the knee by stabilizing the posterior aspect of the fibula over the lateral head of the gastrocnemius with the heel of the other hand. Next, the knee is extended, with the upper hand both supporting the tibia on the lateral side and applying a slight valgus strain. If ACL instability is present, one expects the femur to fall posteriorly, while the tibia plateau subluxes anteriorly. The examiner may slightly internally rotate the leg with the lower hand that is supporting the ankle and leg in order to increase the subluxation. To prevent simple reduction, the subluxed tibia is then impinged against the lateral femoral condyle by applying a strong valgus force to the knee with the upper hand. The knee is then flexed, and a positive test result for the pivot shift test would involve an abrupt reduction of the tibia at approximately 30° flexion. The patient will identify this feeling as the phenomenon of instability that they have been experiencing.

5.4.2 Strengths and Limitations

The pivot shift test is a more challenging test to perform than the previous two maneuvers, especially on patients who are awake, which may result in inaccuracies by an unexperienced reviewer. False-negative test results may arise due to protective muscle action against the subluxation phenomenon. In addition, ACL reattachment to the proximal portion of the PCL or concomitant MCL injuries can limit the amount of valgus force that can be applied to the knee [2, 5].

5.4.3 Accuracy

One meta-analysis of 15 studies all published before the year 2000 with an aggregate sample size of 1,431 patients reported an extremely low pooled sensitivity of 24 % (95 % CI, 21–27 %) [1]. Another meta-analysis of five studies all published after the year 2000 with a total sample size of 948 patients found the sensitivity of the pivot shift test to be 79 % (95 % CI, 63–91 %) [7] (Table 5.1). While the test may not have a high sensitivity, the specificity of the pivot shift test was reported to be very high. A meta-analysis of 15 studies published before 2000 reported a pooled specificity of 98 % (95 % CI, 96–99 %) [1] (Table 5.2). Another systematic review reported LR+ and LR− values with ranges of 4.37–16.42 and 0.38–0.84, respectively, but did not perform a meta-analysis as the authors of the review were concerned with the lack of precision and high risk of bias in all five studies included in the review [15].

5.4.3.1 Type of Injury

Partial ACL tears have been shown to elicit increased false-negative results on the pivot shift examination [2]. A meta-analysis of five studies published after 2000 with an aggregate sample size of 586 patients calculated a pooled sensitivity for complete ACL ruptures of 86 % (95 % CI, 68–99 %). The pooled sensitivity for partial ruptures calculated based on an aggregate of 227 patients was 67 % (95 % CI, 47–83 %) [7]. The decreased sensitivity of the pivot shift test performed on partial ruptures reflects the increased incidence of false-negative results with this type of ACL injury.

5.4.3.2 Effect of Anesthesia

Anesthesia eliminates the effect of muscle guarding which may be responsible for false-negative test results in a patient who is awake. A meta-analysis of 13 studies all published before the year 2000 with an aggregate sample size of 1,077 patients calculated a pooled sensitivity of 74 % (95 % CI, 71–77 %) [1]. The ACL injuries were not differentiated by chronicity or type (partial or complete) in this systematic review. Another meta-analysis of 12 studies (with 11 of these studies included in the previous meta-analysis) reported a pooled sensitivity of acute, complete ruptures under anesthesia of 73 % ($n = 1{,}192$) compared to 28 % without anesthesia ($n = 1{,}094$) [17].

Pivot Shift Test
- Has the highest specificity and thus the most useful in diagnosing ACL injury with a positive test result.
- Older studies indicate very low sensitivity but improved sensitivity noted in newer reports.
- Anesthesia eliminates muscle guarding and significantly improves sensitivity.

References

1. Benjaminse A, Gokeler A, van der Schans CP (2006) Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis. J Orthop Sports Phys Ther 36(5):267–288
2. Donaldson WF 3rd, Warren RF, Wickiewicz T (1985) A comparison of acute anterior cruciate ligament examinations. Initial versus examination under anesthesia. Am J Sports Med 13(1):5–10
3. Draper DO, Schulthies SS (1995) Examiner proficiency in performing the anterior drawer and Lachman tests. J Orthop Sports Phys Ther 22:263–266
4. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop 147:45–50
5. Kim SJ, Kim HK (1995) Reliability of the anterior drawer test, the pivot shift test, and the Lachman test. Clin Orthop Relat Res 317:237–242
6. Lange T, Freiberg A, Dröge P, Lützner J, Schmitt J, Kopkow C (2015) The reliability of physical examination tests for the diagnosis of anterior cruciate ligament rupture – a systematic review. Man Ther 20(3):402–411
7. Leblanc MC, Kowalczuk M, Andruszkiewicz N, Simunovic N, Farrokhyar F, Turnbull TL, Debski RE, Ayeni OR (2015) Diagnostic accuracy of physical examination for anterior knee instability: a systematic review. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-015-3563-2
8. Malanga GA, Andrus S, Nadler SF, McLean J (2003) Physical examination of the knee: a review of the original test description and scientific validity of common orthopedic tests. Arch Phys Med Rehabil 84(4):592–603
9. Mitsou A, Vallianatos P (1988) Clinical diagnosis of ruptures of the anterior cruciate ligament: a comparison between the Lachman test and the anterior drawer sign. Injury 19:427–428
10. Mulligan EP, Harwell JL, Robertson WJ (2011) Reliability and diagnostic accuracy of the Lachman test performed in a prone position. J Orthop Sports Phys Ther 41(10):749–757
11. Paessler HH, Michel D (1992) How new is the Lachman test? Am J Sports Med 20:95–98
12. Sackett DL, Haynes RB, Guyatt GH, Tugwell P (1992) Clinical epidemiology: a basic science for clinical medicine, 2nd edn. Little, Brown and Co, Boston
13. Scholten RJ, Opstelten W, van der Plas CG, Bijl D, Deville WL, Bouter LM (2003) Accuracy of physical diagnostic tests for assessing ruptures of the anterior cruciate ligament: a meta-analysis. J Fam Pract 52: 689–694
14. Strobel M, Stedtfeld HW, Feagin JA, Telger TC (1990) Diagnostic evaluation of the knee. Springer, New York
15. Swain MS, Henschke N, Kamper SJ, Downie AS, Koes BW, Maher CG (2014) Accuracy of clinical tests in the diagnosis of anterior cruciate ligament injury: a systematic review. Chiropr Man Ther 22:25
16. Torg JS, Conrad W, Kalen V (1976) Clinical diagnosis of anterior cruciate ligament instability in the athlete. Am J Sports Med 4:84–93
17. van Eck CF, van den Bekerom MP, Fu FH, Poolman RW, Kerkhoffs GM (2013) Methods to diagnose acute anterior cruciate ligament rupture: a meta-analysis of physical examinations with and without anaesthesia. Knee Surg Sports Traumatol Arthrosc 21:1895–1903

Timing of Pediatric ACL Reconstruction

6

Allen F. Anderson and Christian N. Anderson

6.1 Introduction

The increase in intrasubstance anterior cruciate ligament tears in children and adolescents has intensified the debate about whether the best management of these injuries is nonoperative, early surgical reconstruction, or delayed surgical reconstruction. This management decision must be made in the context of the harms and efficacy associated with each method of treatment.

The unique challenge of treating ACL injuries in skeletally immature patients, combined with the absence of an efficacious surgical procedure, resulted in a historical approach of nonoperative treatment, typically consisting of functional bracing, physical therapy, and activity modification. This treatment choice has several important advantages. Delaying surgery allows for greater skeletal maturation, decreasing the likelihood of growth plate disturbance from physeal injury, and allows for greater psychological maturation of the patient, which increases compliance with postoperative therapy. Despite these advantages, more recent evidence suggests that nonoperative treatment and delayed reconstruction may result in recurrent injury, meniscal damage, chondral injuries, and sports-related disability [3, 6, 8, 9, 14, 17, 21, 23, 24].

Although early reconstruction reduces episodes of instability, meniscal tears, and cartilage injuries, this method of treatment may also cause complications including iatrogenic growth disturbance with leg-length discrepancy or angular deformity [5, 12, 13, 15, 24]. A greater awareness of physeal response to injury has led to the development of anatomic reconstructions that minimize the extent of physeal injury [2].

6.2 Nonoperative and Delayed Surgical Management

The absence of level I studies comparing nonoperative treatment to newer anatomic reconstruction techniques makes it difficult to determine whether nonoperative treatment, early reconstruction or delayed reconstruction, is the best treatment option for ACL tears in pediatric patients. Several small, level-of-evidence (LOE) 4 studies indicate that nonoperative treatment or delayed reconstruction until skeletal maturity results in poor outcomes [1, 7, 10, 11, 16, 18, 22]. Even so, other studies with similar designs support the use of a nonoperative treatment algorithm in skeletally immature patients [25]. Consequently, in the older literature, surgeons may find support for any method of treatment.

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6.2.1 Delay of Surgery 6–12 Weeks

Recently, several studies with a higher level of evidence have evaluated the consequences associated with delay in ACL reconstruction. In a study of 39 pediatric patients with an average age of 13.6 years, Millet et al. [17] (LOE 3) compared the concurrent injuries in a cohort of patients who had acute reconstructions (less than 6 weeks) to another cohort who had chronic reconstructions (more than 6 weeks). A highly significant relationship was found between the time of surgery and medial meniscus tears. Thirty-six percent of patients in the chronic cohort sustained medial meniscus tears compared to only 11 % in the acute cohort. Lawrence et al. [14], in a (LOE 3) cohort study of 70 patients, found with logistic regression analysis that time to surgical reconstruction greater than 12 weeks (odds ratio 4.1) and a single episode of knee instability (odds ratio 11.4) were independently associated with medial meniscal tears. Time to surgery was also independently associated with medial and lateral compartment chondral injuries (odds ratio 5.6 and 11.3, respectively).

Anderson and Anderson [3], in a (LOE 3) study of 135 patients, found that delay in reconstruction increased the risks of secondary meniscal and chondral injury. Sixty-two patients were treated with ACL reconstruction within 6 weeks, 37 had surgery between 6 and 12 weeks, and 36 were treated after 12 weeks. Increased time to surgery had a bivariate association with lateral and medial meniscal tears ($p=0.016$ and 0.007, respectively). Independent risk factors for incidence of lateral meniscal tears were younger age ($p=0.028$) and return to sports activity before surgery ($p=0.007$). Patients with one episode of recurrent instability had threefold higher odds of a higher grade of lateral meniscal tears. Compared with acute reconstruction, subacute and chronic reconstruction patients had 1.45 and 2.82 times higher odds, respectively, of lateral meniscal tears severity ($p=0.012$). Another correlate of severity of lateral meniscal tears was any episode recurrent instability (odds ratio = 3.15). Independent risk factors for the incidence of medial meniscal tears were older age ($p=0.01$) and any recurrent instability episode ($p=0.01$). The odds ratio for increased severity of medial meniscal tears include any recurrent instability episodes (odds ratio 5.6), playing sports before reconstruction (odds ratio 15.2), and time to surgery greater than 3 months (odds ratio 4.3). Seventeen patients had 23 chondral injuries in this cohort. The risk factors for increased incidence and grade of chondral injuries included time to surgery ($p=0.005$) and any recurrent instability episodes ($p=0.001$).

In a LOE 3 study, Newman and coworkers compared patients less than 14 years old to those 14–19 years old to identify factors related to the presence of concomitant injuries at the time of ACL reconstruction. They found a significant relationship between time to surgery and the development of an irreparable meniscal injury ($p \leq 0.05$) in both younger and older patients. Time to surgery correlated with severity of chondral injuries in the young cohort ($p=0.03$) but not the older cohorts ($p=0.88$). In the younger cohort, only a delay in surgery greater than 3 months (odds ratio = 4.8; $p=0.003$) was significantly predictive of the presence of an injury that required an additional operative procedure. In the older patients, return to activity before surgery (odds ratio 3.8; $p=0.003$) and obesity (odds ratio 2.5; $p=0.038$) were significantly predictive of an injury that required additional operative procedures. They concluded that a delay in surgery correlated with increased severity of injury among both older and younger patients. A delay in surgery greater than 3 months was the strongest predictor of the development of concomitant injuries in the younger cohorts.

6.2.2 Delay in Surgery at Least 6 Months

Other studies have evaluated additional injuries when ACL reconstruction was delayed for at least 6 months after the initial injury. Henry et al. [9], in a retrospective study of 56 patients (LOE 2), compared concurrent injuries with surgery delayed by a mean of 30 months to those who had surgery delayed by 13.5 months. They found a statistically higher rate of medial meniscal tears (41 % vs 16 %) and lower subjective IKDC scores (83.4 vs 94.6) in those with surgery delayed by 30 months. Dumont et al. [4] (LOE 3) evaluated the incidence of meniscal and chondral injuries in patients undergoing early (less than 150 days; $n = 241$) compared to delayed ACL reconstruction (greater than 150 days; $n = 129$). Medial meniscal tears were significantly more common in the delayed treatment group (37.8 % vs 53.5 %; odds ratio 1.8; $p = 0.014$), but the incidence of lateral meniscal tears was similar between groups. They also found that patients with meniscal tears were more likely to have chondral injuries in the same compartment. Guenther and colleagues [8] conducted a retrospective review (LOE 4) of 112 adolescents with a mean age of 15 years. A comparison of MRI findings after the initial injury (mean 79 days) with surgical findings at the time of reconstruction (mean 342 days) showed patients new or worsened medial meniscal tears had waited significantly longer for surgery (445 vs 290 days). Additionally, bucket-handle meniscal tears increased steadily in frequency for more than a year after ACL injury.

In contrast to the findings of these studies, a few studies have found that delayed reconstruction is a reasonable option. Woods and O'Connor [25] (LOE 4) compared a group of 13 adolescents with a mean age of 13.8 years at the time of injury who had surgery delayed for a mean of 70 weeks to a group of 116 adolescents with a mean age of 15 years. The skeletally mature group had a mean time interval from the injury to surgery of 14.1 (0.3–355) weeks. The rate of meniscal injuries was 20 % higher, and the number of irreparable medial meniscal tears was greater when surgery was delayed by 6 months. The rate of additional knee surgeries was 62 % when surgery was delayed by more than 6 months and 27 % when surgery was performed within 6 months. Despite these differences, the authors concluded that there was no significant difference with respect to meniscal and chondral injuries between the groups, although they admitted that one of the limitations was the lack of statistical power due to the small sample sizes.

Another study of Moksnes et al. [20] compared 20 children aged 12 years old, or younger, treated nonoperatively to 6 children who had delayed reconstruction. Of the nonoperative group, 65 % returned to their pre-injury activity level and 50 % were classified as copers at follow-up. Only 9.5 % of the non-copers had secondary meniscal injuries. Based on the large number of copers in the nonoperative group and relatively low number of meniscal injuries, a treatment algorithm based on function and patient satisfaction was suggested that may identify patients who could participate in sports activities until skeletal maturity when ACL reconstruction would be considered.

In a follow-up (LOE 4) study of this algorithm [19], the same authors evaluated 40 children with 3.0-T MRI at the time of injury and 3.8 years later. Patients in this cohort had a 19.5 % chance of developing a meniscal tear not related to initial injury. Ultimately, 32 % had ACL reconstruction due to recurrent instability, meniscal injury, and significant reduction of activity level. The authors recommended further follow-up to evaluate the long-term knee health in these children.

Fundahashi et al. [6], in a (LOE 3) study conducted at a large integrated health system, evaluated 71 patients after treatment with activity restrictions until skeletal maturity. Forty-seven patients (66 %) had surgery at an average time of 16.6 months after injury. At the time of surgery, 57 % had meniscal injuries and 51 % had both meniscal and chondral injuries. They found no association between the time to surgery and meniscal and cartilage injury, but there was a positive association between the number of "significant encounters" (return for new pain or swelling) and the likelihood of combined chondral and meniscal injuries ($p = 0.01$).

A recent meta-analysis and a systematic review evaluated the literature to determine the harms associated with nonoperative treatment or delay in surgical reconstruction. Vavken and Murray [24] systematically reviewed the current evidence for nonoperative and surgical treatment of ACL tears in skeletally immature patients (Table 6.1). They identified 47 studies that met

Table 6.1 Review of studies on timing of ACLR in skeletally immature patients

Author	Study type	Patients	Outcomes
Newman (*AJSM* 2015) [21]	Cohort study (LOE 3)	Older cohort (14–19 y/o; ($n=165$) Younger cohort (<14 y/o; $n=66$)	Significant relationship between time to ACLR and irreparable meniscal pathology in both groups *Young cohort:* Time to surgery correlated to severity of chondral injury Delay in surgery >3 months predictive of the presence of an injury that required additional operative procedures *Older cohort:* Return to activity before surgery and obesity predictive of an injury that required additional operative procedures
Anderson (*AJSM* 2015) [3]	Cohort study (LOE 3)	Acute group (ACLR < 6 weeks; $n=62$; median 14 y/o) Subacute group (ACLR 6–12 weeks; $n=37$; median 13 y/o) Chronic Group (ACLR > 12 weeks; $n=36$; median 12 y/o)	Subacute and chronic groups had 1.45 and 2.82 times higher odds, respectively, of LMTs severity compared with acute reconstruction Chronic group was significantly more likely to have increased severity of MMTs Time to surgery was a significant risk factor for increased incidence and grade of chondral injury
Fundahashi(*AJSM* 2014) [6]	Cohort study (LOE 3)	Non-op group ($n=24$; mean age 12.9) Delayed ACLR group ($n=47$; mean age 13.5 y; mean time to surgery 16.6 months)	*Delayed ACLR group:* No significant difference in meniscal/chondral injury if ACLR was delayed <1 year vs. >1 year 57 % had meniscal and 51 % had meniscal and chondral injuries at the time of surgery Patients had average of 4.6 "new encounters" for new pain or swelling Found a positive association between the number of new encounters and likelihood of combined chondral and meniscal injuries
Ramski (*AJSM* 2014) [13]	Meta-analysis (LOE 3)	6 studies compared operative to non-op (total patients, $n=217$) 5 studies compared early to delayed ACLR (total patients, $n=353$)	Nonoperative or delayed treatment was associated with a 34-fold increase in knee instability 2 studies demonstrated patients were over 12 times more likely to have a MMT after nonoperative treatment compared to ACLR 2 studies reported none of the patients in the nonoperative groups returned to their previous level of play compared with 85.7 % of patients in the operative groups

Dumont (*AJSM* 2012) [4]	Cross-sectional study (LOE 3)	Early ACLR (<150 days; $n=241$) Delayed ACLR (>150 days; $n=129$)	Significantly increased MMTs (53.5 % vs. 37.8 %; OR 1.8) and medial tibial cartilage injuries (7.8 % versus 2.1 %) were observed in the delayed treatment group Similar incidence of LMTs was observed between groups Chondral injury was significantly associated with the presence of meniscal tear in the same compartment of the knee
Lawrence (*AJSM* 2011) [14]	Cohort study (LOE 3)	Early ACLR (<12 weeks; $n=41$) Delayed ACLR (>12 weeks; $n=29$) Mean age 12.9 y	Time to surgery >12 weeks was independently associated with MMTs (odds ratio 4.1), as well as medial (OR 5.6) and lateral (OR 11.3) chondral injuries Delay in treatment of >12 weeks was associated with an increase in the severity of MMTs
Henry (*KSSTA* 2009) [9]	Cohort study (LOE 2)	Early ACLR (mean 13.5 months; $n=29$; mean age 11.5 y) Delayed ACLR (mean 30 months; $n=27$; mean age 13.3 y)	Delayed ACLR group had higher rate of medial meniscal tears (41 % vs. 16 %) and higher rate of meniscectomy Both groups had similar rate of lateral meniscus tears Lower subjective IKDC scores (83.4 vs. 94.6) were observed with delayed ACLR
Millett (*Arthroscopy* 2002) [17]	Cohort study (LOE 3)	Acute (<6 week until ACLR; $n=17$) Chronic (>6 weeks until ACLR; $n=22$) Mean age 13.6 y	Found significantly increased meniscus tears when ACLR delayed >6 weeks (36 %) compared to ACLR <6 weeks (11 %) No difference between groups regarding lateral meniscal tears

LOE level of evidence, *ACLR* anterior cruciate ligament reconstruction, *LMT* lateral meniscus tear, *MMT* medial meniscus tear, *OR* odds ratio the inclusion criteria. Nonoperative treatment was found to result in poor clinical outcomes and a higher incidence of secondary defects, including meniscal and chondral injuries. They concluded that surgical stabilization should be considered the preferred treatment and nonoperative treatment should only be considered as a last resort.

Ramski et al. [23], in a meta-analysis, systematically analyzed aggregated data from the literature to determine if superiority of treatment outcomes exists for nonoperative or early operative treatment for ACL tears in pediatric patients. They found six studies (217 patients) that compared operative to nonoperative treatment and five studies (353 patients) that compared early to delayed ACL reconstruction. Three studies reported that posttreatment instability occurred in 13.6 % of patients after operative treatment and 75 % of patients after nonoperative treatment ($p \leq 0.01$). Two studies found symptomatic medial meniscal tears were 12 times more likely after nonoperative treatment ($p = 0.02$). Two additional studies reported return to activity; none of the patients in the nonoperative group returned to previous activity level of play compared to 85.7 % of patients who were treated operatively ($p \leq 0.01$). The authors concluded that multiple trends favor early surgical stabilization over nonoperative or delayed treatment in pediatric ACL tears.

6.3 Growth Disturbance

Although there is a growing body of evidence indicating that nonoperative treatment is associated with meniscal and chondral injuries and sports-related disability, the decision to perform surgery depends on the risk and efficacy of the alternative, surgical reconstruction. Most authors have not reported growth disturbance after physeal sparing ACL reconstruction in pediatric patients; however, Frosch et al. [5], in a meta-analysis of 55 studies including 935 patients who had either a physeal sparing, partial physeal sparing, or transphyseal reconstruction, found that the risk of leg-length discrepancy or angular deformity after surgical treatment was 1.8 %. In the systematic review of 31 studies ($n = 479$ patients), Vavken and Murray [24] found that three patients developed angular defects and two had leg-length discrepancies. They also analyzed the literature to determine if surgical treatment was the best option for pediatric ACL tears. Nine studies with evidence level 2 or 3 compared surgical treatment to nonsurgical treatment ($n = 6$), immediate with delayed reconstruction ($n = 2$), and surgical treatment with mature versus immature patient ($n = 1$). These studies unanimously reported significantly better clinical scores and knee laxity after surgical reconstruction compared to nonoperative treatment. They also found no difference in the risk of growth disturbance.

The risk of growth disturbance in skeletally immature patients can theoretically be minimized by using physeal sparing reconstruction techniques [2]. The all-epiphyseal technique utilizes anatomic tunnels drilled completely within the epiphysis, which decreases the chance of growth disturbance by not transgressing either the tibial or femoral physis (OrthoPediatrics, Warsaw, IN). In order to avoid iatrogenic physeal damage during tunnel placement, there are several important technical factors to consider. The femoral guidewire is placed using C-arm fluoroscopy in the AP plane with appropriate visualization of the physis (Fig. 6.1). The guidewire should be placed sufficiently distal to the femoral physis before advancement into the ACL footprint within the intercondylar notch (Fig. 6.1a). The handle of the guide is elevated 30–40° anteriorly during guidewire placement so the lateral collateral ligament and popliteus tendon attachments on the femur are not damaged during tunnel reaming (Fig. 6.1b). The appropriately sized reamer can be placed over the guidewire to confirm the femoral tunnel will be distal to and not encroach upon the physis.

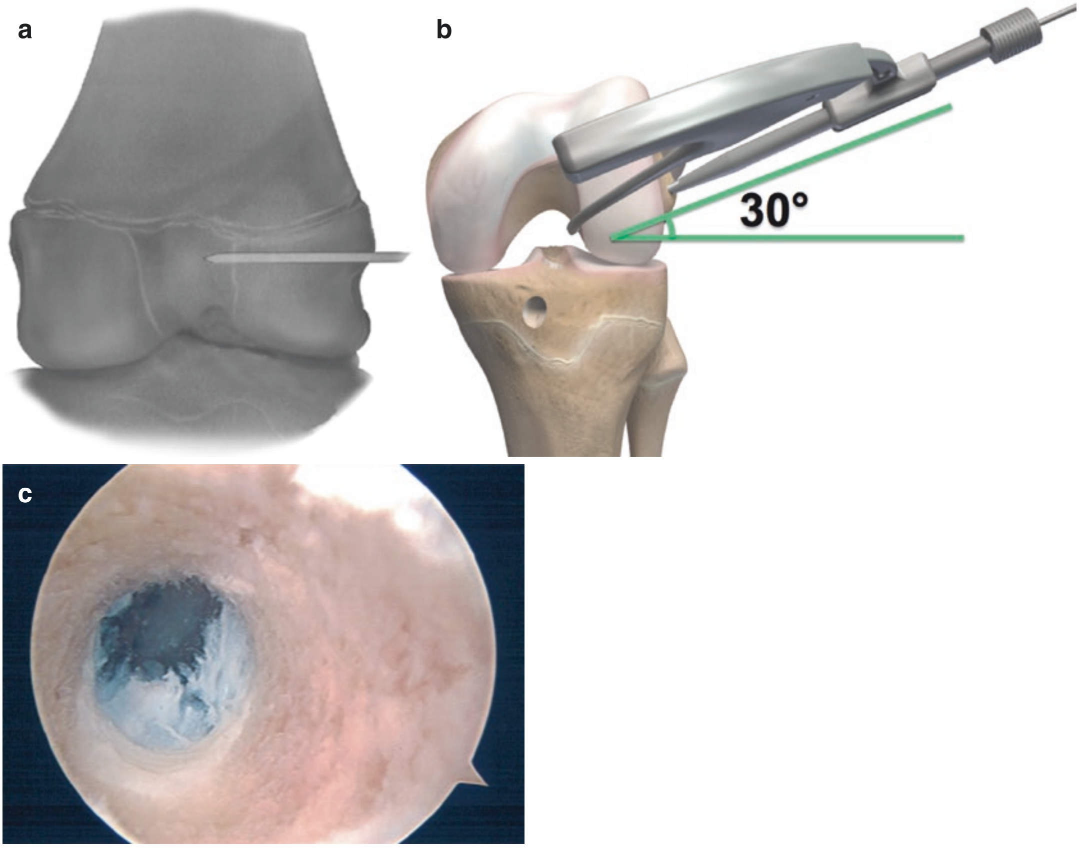

Fig. 6.1 (**a**) The femoral guide wire is placed with the C-arm in the AP plane. The guide wire should be sufficiently distal to the physis to avoid iatrogenic injury during tunnel reaming. (**b**) Elevating the guide 30–35° anteriorly allows the tunnel to avoid the femoral insertions of the LCL and popliteus. (**c**) The femoral tunnel can be inspected by placing the arthroscope into the tunnel from outside in to ensure physeal encroachment did not occur during reaming (Figure **a**, in: *JBJS Am* 2004, September; 86A Supplement 1 (Part 2):201–9 with permission; Figure **b**: (Copyright 2013 OrthoPediatrics Corp., with permission.)

The tunnel is reamed using live fluoroscopy and can be arthroscopically visualized from outside in order to demonstrate adequate bony walls without physeal injury (Fig. 6.1c). The tibial guidewire is placed with the C-arm rotated approximately 30° in the lateral plane, which assists in visualizing the physis extending into the tibial tubercle (Fig. 6.2a). The guidewire is positioned on the anteromedial tibial epiphysis between the physis and joint surface and advanced using real-time fluoroscopic imaging through the epiphysis into the tibial footprint (Fig. 6.2a, b). Reaming of the tibial tunnel is also performed using live fluoroscopy to ensure encroachment on the growth plate does not occur. The graft is then shuttled from distal to proximal and fixed within the epiphysis, thereby avoiding tension across the physis (Fig. 6.2c).

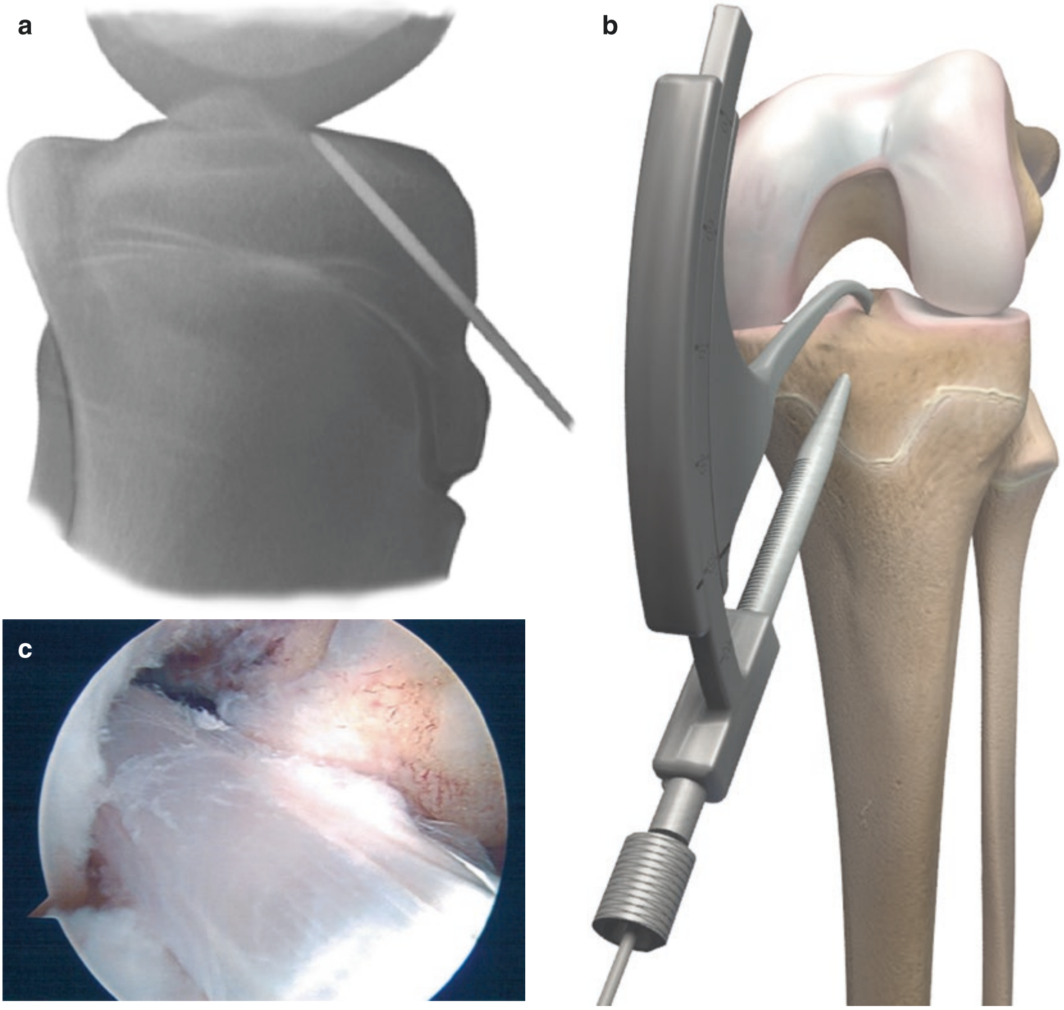

Fig. 6.2 (**a**) The tibial physis is visualized with the C-arm rotated 30° in the lateral plane. (**b**) The guide wire is placed equidistant from the joint surface and tibial physis on the anteromedial epiphysis. (**c**) Arthroscopic view of the graft after fixation (Figure **a**, in: *JBJS Am* 2004, September; 86A Supplement 1 (Part 2):201–9 with permission; Figure **b**: (Copyright 2013 OrthoPediatrics Corp., with permission.)

Conclusion

Ideally, operative treatment of ACL injuries in skeletally immature patients could be postponed until physeal closure. Most of the evidence, however, indicates that nonoperative treatment may actually result in substantial risks to the knee. In contrast, current methods of ACL reconstruction are highly effective in preventing additional injuries and sports-related disability. Consequently, the treatment of choice for pediatric ACL tears is early reconstruction (within 3 months), although it is important for the patient to have regained knee extension and near-normal flexion before surgery to minimize the risk of postoperative arthrofibrosis.

References

1. Aichroth PM, Patel DV, Zorrilla P (2002) The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents: a prospective review. J Bone Joint Surg (Br) 84:38–41

2. Anderson AF (2003) Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients: a preliminary report. J Bone Joint Surg Am 85:1255–1263
3. Anderson AF, Anderson CN (2015) Correlation of meniscal and articular cartilage injuries in children and adolescents: timing. ACL Reconstr Am J Sports Med 43(2):275–281
4. Dumont G, Hogue G, Podalecki J (2012) Meniscal and chondral injuries associated with pediatric anterior cruciate ligament tears: relationship of treatment time and patient-specific factors. Am J Sports Med 40(9):2128–2133
5. Frosch KH, Stengel D, Brodhun T et al (2010) Outcomes and risks of operative treatment of rupture of anterior cruciate ligament in children and adolescents. Arthroscopy 26:1539–1550
6. Fundahashi KM, Moksnes H, Maletis GB et al (2014) Anterior cruciate ligament injuries in adolescents with open physes: effect of recurrent injury and surgical delay on meniscal and cartilage injuries. Am J Sports Med 42(5):1068–1073
7. Graf BK, Lange RH, Fujisaki CK et al (1992) Anterior cruciate ligament tears in skeletally immature patients: meniscal pathology at presentation and after attempted conservative treatment. Arthroscopy 8: 229–233
8. Guenther Z, Swami V, Dhillon S, Jaremko J (2014) Meniscal injury after adolescent anterior cruciate ligament injury: how long are patients at risk? Clin Orthop Relat Res 472:990–997
9. Henry J, Chotel F, Chouteau J et al (2009) Rupture of the anterior cruciate ligament in children: early reconstruction with open physes or delayed reconstruction to skeletal maturity? Knee Surg Sports Traumatol Arthrosc 17:748–755
10. Janarv PM, Nystrom A, Werner S, Hirsch G (1996) Anterior cruciate ligament injuries in skeletally immature patients. J Pediatr Orthop 16:673–677
11. Kannas P, Jarvinen M (1988) Knee ligament injury in adolescents, eight year follow-up of conservative management. J Bone Joint Surg 70:772–776
12. Kocher MS, Saxon HS, Hovis WD et al (2002) Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and the ACL Study Group. J Pediatr Orthop 22:452–457
13. Koman JD, Sanders JO (1999) Valgus deformity after reconstruction of the anterior cruciate ligament in skeletally immature patients: a case report. J Bone Joint Surg Am 81:711–715
14. Lawrence JT, Argawal N, Ganley TJ (2011) Degeneration of the knee joint in skeletally immature patients with a diagnosis of an anterior cruciate ligament tear: is there harm in delay of treatment? Am J Sports Med 39(12):2582–2587
15. Lipscomb AB, Anderson AF (1986) Tears of the anterior cruciate ligament in adolescents. J Bone Joint Surg Am 68:19–28
16. McCarroll JR, Rettig AC, Shelbourne KD (1988) Anterior cruciate ligament injuries in the young athlete with open physes. Am J Sports Med 16:44–47
17. Millett PJ, Willis AA, Warren RF (2002) Associated injuries in pediatric and adolescent anterior cruciate ligament tears: does a delay in treatment increase the risk of Meniscal Tear? Arthroscopy 18:955–959
18. Mizuta H, Kubota K, Shiraishi M et al (1995) The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. J Bone Joint Surg (Br) 77:890–894
19. Moksnes H, Engebretsen L, Risberg MA (2013) Prevalence and incidence of new meniscus and cartilage injuries after a nonoperative treatment algorithm for ACL tears in skeletally immature children: a prospective MRI study. Am J Sports Med 41(8):1771–1779
20. Moksnes H, Engebretsen L, Risberg MA (2008) Performance-based functional outcome for children 12 years or younger following anterior cruciate ligament injury: a two to nine-year follow-up study. Knee Surg Sports Traumatol Arthrosc 16:214–223
21. Newman JT, Carry PM, Terhune B et al (2015) Factors predictive of concomitant injuries among children and adolescents undergoing anterior cruciate ligament surgery. Am J Sports Med 43(2):282–288
22. Pressman AE, Lets RM, Jarvis JG (1997) Anterior cruciate ligament tears in children: an analysis of operative versus nonoperative treatment. J Pediatr Orthop 17:505–511
23. Ramski D, Franklin C, Baldwin K, Ganley T (2014) Anterior cruciate ligament tears in children and adolescents: a meta-analysis of nonoperative versus operative treatment. Am J Sports Med 42(11):2769–6
24. Vavken P, Murray M (2011) Treating anterior cruciate ligament tears in skeletally immature patients. Arthroscopy 27(5):704–716
25. Woods GW, O'Connor DP (2004) Delayed anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med 32:201–210

Conservative Treatment of Pediatric ACL Injury

7

Lars Engebretsen and Håvard Moksnes

7.1 Introduction

The number of publications on treatment of ACL injuries in the skeletally immature population has increased through the past decade [5, 6, 8, 12, 18, 20, 26]. However, opinions on whether pediatric ACL treatment should primarily be surgically reconstructed or conservatively treated are still divided within the pediatric orthopedic community [25, 33]. Evidence from high level studies and randomized controlled trials are lacking [28], which leave the field open for various treatment algorithms due to the lack of a solid scientific knowledge base [31]. Risk factors for ACL injuries in skeletally immature patients are unknown, although it seems that boys may be more prone to rupturing their ACL before skeletal maturity, while girls have an increased risk through and after puberty [11, 34]. Many authors argue that the incidence of pediatric ACL injuries is rising [2, 6, 10, 17]; however, no epidemiological studies are available to support this statement. Increased awareness and advances in diagnostic methods, in addition to higher participation rates and earlier specialization in sports, may have led to an increase in the incidence of pediatric ACL tears.

7.2 Treatment Decision-Making

Weighing of the risks and benefits between primary surgical treatment and primary active rehabilitation without surgical intervention is crucial for every surgeon involved in pediatric ACL decision-making [29]. Over the past decade, our group has followed a primary nonoperative treatment algorithm (Fig. 7.1) [29]. This prevents skeletal growth problems as complications from surgery and has led to approximately 2/3 of the patients treated with rehabilitation only until they reach full skeletal maturity. This algorithm highlights the post-injury rehabilitation to be performed exhaustively before further treatment decisions are taken, based on the functional knee stability experienced by the child in its desired activities and through functional performance tests. There is substantial support in the literature that supervised rehabilitation should be performed before a decision on further treatment is made for an ACL patient

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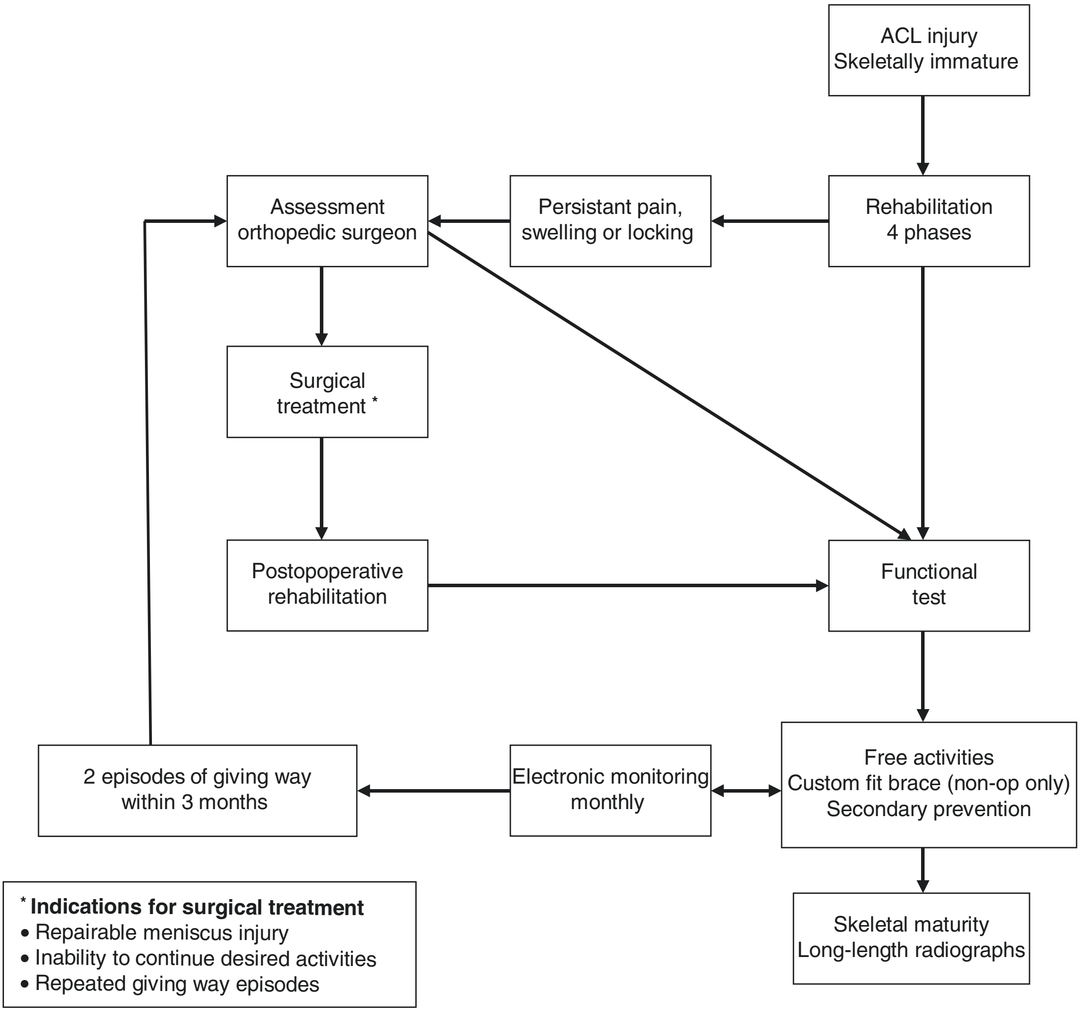

Fig. 7.1 The treatment algorithm for anterior cruciate ligament injury in skeletally immature children [29]

[19, 24]. Preoperative rehabilitation is beneficial because it increases the likelihood of a successful outcome after ACL reconstruction and is in many cases effective in restoring functional knee stability to a level that eliminates the need for a surgical ACL reconstruction [13, 21]. We argue that children with ACL injuries should be monitored and assessed by an orthopedic surgeon and a physical therapist working together, securing that a structured rehabilitation program has been successful or not to provide functional stability of the individual knee before any surgical treatment is initiated.

In our prospective cohort study on 46 skeletally immature children, we found that two thirds were able to continue their activities for at least 2 years without suffering of instability or secondary injuries that required surgical treatment [26, 30]. This study is to date the only prospective study on conservative management of ACL injured children 12 years or younger. To our knowledge, no other well-designed studies on nonoperative management have been published, and the rates of secondary meniscus injuries in three out of four case series are low [23, 27, 37]. However, caution must be taken with regard to the long-term results. Likewise, there is a need for prospective studies with objective functional outcome measures on surgical treatment in this population.

7.3 Rehabilitation Progression

Pediatric rehabilitation has to be performed in close collaboration between the parents, an experienced physiotherapist, and the orthopedic surgeon. Exercises and goals have to be adjusted compared to traditional rehabilitation protocols because children cannot be expected to perform unsupervised training independently. Rehabilitation exercises are less focused on muscular strength and hypertrophy, while the primary focus should be neuromuscular stimulation and maintenance of multi-joint functional stability [9, 29]. Inability to be active in preferred activities or repetitive episodes of giving way despite undergoing an adequate rehabilitation program will point toward advising an ACL reconstruction before skeletal maturity. Additionally, children who have a secondary repairable meniscus injury will usually undergo a meniscus repair with concomitant ACL reconstruction, as this is assumed to improve the prognosis of the meniscus repair [14]. We also find it imperative that the child and parents are provided with thorough information on the benefits and risks involved with both surgical and conservative treatment, including the option of continuing sports involving less pivoting motions until skeletal maturity is reached, when a reconstruction involving less risk can be performed.

Modern rehabilitation is progressed through phases or stages based on sound clinical reasoning, sequenced functional achievements, and the completion of functional milestones. At the same time, knowledge on tissue-specific biologic healing processes should be respected and will guide the timeline of progression. Throughout the rehabilitation process, a structure with four phases is often used to guide the aims and content of the progression (Fig. 7.2). Within each phase, specific functional milestones and achievement goals are identified. Some goals will be primary in each phase, for example, achieving full knee extension and quadriceps activation early after the knee injury in phase 1. Throughout the first two phases, the child should be guarded from pivoting activities and possibly also wear a protective brace in school and training. Exercises to facilitate proper alignment and adequate landing techniques have been successfully implemented in injury prevention programs [15, 22, 36] and are recommended through phase 2 and 3 of pediatric ACL rehabilitation.

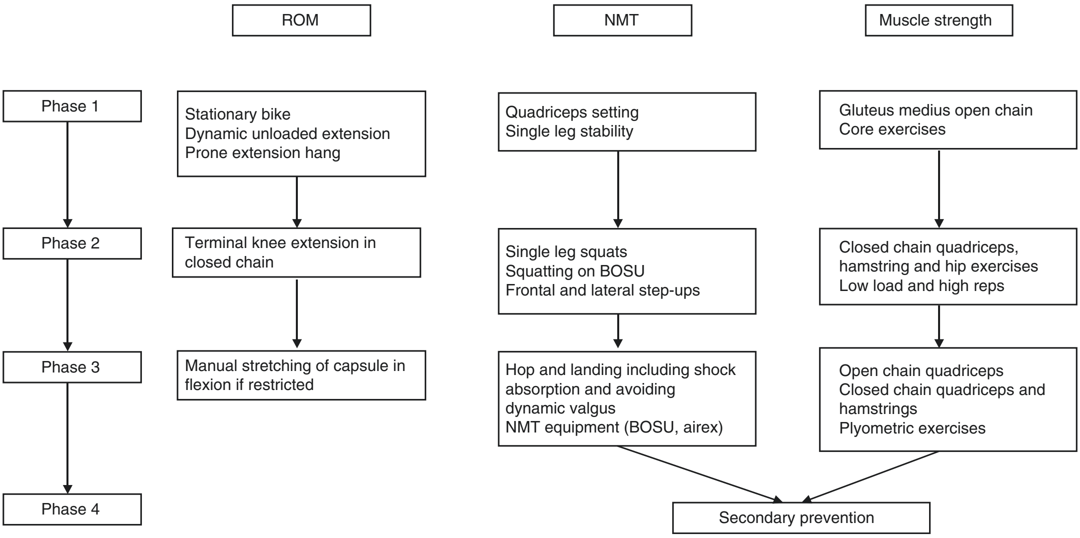

Fig. 7.2 Proposed guide for the rehabilitation of anterior cruciate ligament injury in skeletally immature individuals (ROM, range of motion; NMT, neuromuscular training) [29]

The child and parents should consult their physical therapist regularly. A normal setup could be once a week throughout phase 1, every second week through phase 2, and once a month in phase 3. Rehabilitation usually should be designed to enable performance at home, and it is recommended to limit the number of exercises to enhance the feasibility and adherence to the program [7].

Phase 1 In line with the increased focus on active rehabilitation strategies, the newly proposed acronym POLICE (protection, optimal loading, ice, compression, and elevation) should be implemented [4]. In the acute phase, the primary goals are to regain active and passive knee extension, resolve intra-articular swelling, and to reactivate the quadriceps muscle. Dynamic open-chain unloaded extension exercises, stationary cycling, prone knee extension hang, and partial weight bearing with normal gait cycle are performed to achieve the rehabilitation milestones of straight leg raises without extension lag, ability to perform weight-bearing single-leg terminal extension, and unrestricted normal gait patterns.

Phase 2 The primary goal is to normalize activities of daily living. Neuromuscular exercises focusing on dynamic control of the terminal knee extension in single-leg stance, step-up, and squatting exercises while avoiding dynamic valgus [15]. Closed-chain quadriceps and hamstring exercises are included to facilitate appropriate motor firing and recruitment. Milestones in phase 2 are normal stair ascent and descent and ability to participate in daily activities without experiencing instability or intra-articular swelling.

Phase 3 The primary goal is to normalize running and to develop the ability of maintaining knee stability through single-leg hops. External tasks are added to the exercises to autotomize the strategies for joint stability. Two- and single-leg hops are initially performed with focus on safe landings with optimal trunk, hip, and knee alignment. Hop exercises are progressed to multi-hop plyometrical movements with stops and cuts. Neuromuscular training with equipment such as BOSU balls are frequently incorporated in the exercises. Additionally, functional quadriceps and hamstring strength exercises are performed as home exercises without external load. Children are allowed return to their preferred activities wearing a custom-fit functional knee brace when they can perform a single-leg hop test battery with at least 90 % of the values on the uninjured side [3, 16].

Phase 4 The fourth phase includes a selection of neuromuscular exercises focusing on maintaining functional stability as a secondary prevention measure. Ideally, these exercises should be performed as part of their team warm-up routine before practice which has been shown to be effective in preventing lower extremity injury rates by as much as 50 % [1, 32, 35]. Several online resources are freely available such as the “Get Set – Train Smarter” app and the www.skadefri.no website.

References

1. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc 17(7):705–729
2. Anderson AF, Anderson CN (2015) Correlation of meniscal and articular cartilage injuries in children and adolescents with timing of anterior cruciate ligament reconstruction. Am J Sports Med 43(2): 275–281
3. Barber-Westin SD, Noyes FR (2011) Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. Phys Sportsmed 39(3):100–110
4. Bleakley CM, Glasgow P, MacAuley DC (2012) PRICE needs updating, should we call the POLICE? Br J Sports Med 46(4):220–221
5. Calvo R, Figueroa D, Gili F, Vaisman A, Mococain P, Espinosa M, Leon A, Arellano S (2015) Transphyseal anterior cruciate ligament reconstruction in patients with open physes: 10-year follow-up study. Am J Sports Med 43(2):289–294
6. Demange MK, Camanho GL (2014) Nonanatomic anterior cruciate ligament reconstruction with double-stranded semitendinosus grafts in children with open physes: minimum 15-year follow-up. Am J Sports Med 42(12):2926–2932

7. Faber M, Andersen MH, Sevel C, Thorborg K, Bandholm T, Rathleff M (2015) The majority are not performing home-exercises correctly two weeks after their initial instruction-an assessor-blinded study. PeerJ 3:e1102
8. Fabricant PD, Jones KJ, Delos D, Cordasco FA, Marx RG, Pearle AD, Warren RF, Green DW (2013) Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: a review of current concepts: AAOS exhibit selection. J Bone Joint Surg Am 95(5):e28
9. Faigenbaum AD, Kraemer WJ, Blimkie CJ, Jeffreys I, Micheli LJ, Nitka M, Rowland TW (2009) Youth resistance training: updated position statement paper from the national strength and conditioning association. J Strength Cond Res 23(5 Suppl):S60–S79
10. Frosch KH, Stengel D, Brodhun T, Stietencron I, Holsten D, Jung C, Reister D, Voigt C, Niemeyer P, Maier M, Hertel P, Jagodzinski M, Lill H (2010) Outcomes and risks of operative treatment of rupture of the anterior cruciate ligament in children and adolescents. Arthroscopy 26(11):1539–1550
11. Funahashi KM, Moksnes H, Maletis GB, Csintalan RP, Inacio MC, Funahashi TT (2014) Anterior cruciate ligament injuries in adolescents with open physis: effect of recurrent injury and surgical delay on meniscal and cartilage injuries. Am J Sports Med 42(5): 1068–1073
12. Goddard M, Bowman N, Salmon LJ, Waller A, Roe JP, Pinczewski LA (2013) Endoscopic anterior cruciate ligament reconstruction in children using living donor hamstring tendon allografts. Am J Sports Med 41(3):567–574
13. Grindem H, Granan LP, Risberg MA, Engebretsen L, Snyder-Mackler L, Eitzen I (2015) How does a combined preoperative and postoperative rehabilitation programme influence the outcome of ACL reconstruction 2 years after surgery? A comparison between patients in the Delaware-Oslo ACL Cohort and the Norwegian National Knee Ligament Registry. Br J Sports Med 49(6):385–389
14. Heckmann TP, Barber-Westin SD, Noyes FR (2006) Meniscal repair and transplantation: indications, techniques, rehabilitation, and clinical outcome. J Orthop Sports Phys Ther 36(10):795–814
15. Hewett TE, Ford KR, Myer GD (2006) Anterior cruciate ligament injuries in female athletes: part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. Am J Sports Med 34(3):490–498
16. Johnsen MB, Eitzen I, Moksnes H, Risberg MA (2015) Inter- and intrarater reliability of four single-legged hop tests and isokinetic muscle torque measurements in children. Knee Surg Sports Traumatol Arthrosc 23(7):1907–1916
17. Kaeding CC, Flanigan D, Donaldson C (2010) Surgical techniques and outcomes after anterior cruciate ligament reconstruction in preadolescent patients. Arthroscopy 26(11):1530–1538
18. Kim SJ, Shim DW, Park KW (2012) Functional outcome of transphyseal reconstruction of the anterior cruciate ligament in skeletally immature patients. Knee Surg Relat Res 24(3):173–179
19. Kruse LM, Gray BL, Wright RW (2011) Anterior cruciate ligament reconstruction rehabilitation in the pediatric population. Clin Sports Med 30(4):817–824
20. Kumar S, Ahearne D, Hunt DM (2013) Transphyseal anterior cruciate ligament reconstruction in the skeletally immature: follow-up to a minimum of sixteen years of age. J Bone Joint Surg Am 95(1):e1
21. Lynch AD, Logerstedt DS, Grindem H, Eitzen I, Hicks GE, Axe MJ, Engebretsen L, Risberg MA, Snyder-Mackler L (2015) Consensus criteria for defining 'successful outcome' after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. Br J Sports Med 49(5):335–342
22. McKay CD, Steffen K, Romiti M, Finch CF, Emery CA (2014) The effect of coach and player injury knowledge, attitudes and beliefs on adherence to the FIFA 11+ programme in female youth soccer. Br J Sports Med 48(17):1281–1286
23. Mizuta H, Kubota K, Shiraishi M, Otsuka Y, Nagamoto N, Takagi K (1995) The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. J Bone Joint Surg Br 77(6):890–894
24. Mohtadi N, Grant J (2006) Managing anterior cruciate ligament deficiency in the skeletally immature individual: a systematic review of the literature. Clin J Sport Med 16(6):457–464
25. Moksnes H, Engebretsen L (2015) It takes more than timing: letter to the editor. Am J Sports Med 43(6): NP14–NP15
26. Moksnes H, Engebretsen L, Eitzen I, Risberg MA (2013) Functional outcomes following a non-operative treatment algorithm for anterior cruciate ligament injuries in skeletally immature children 12 years and younger. A prospective cohort with 2 years follow-up. Br J Sports Med 47(8):488–494
27. Moksnes H, Engebretsen L, Risberg MA (2008) Performance-based functional outcome for children 12 years or younger following anterior cruciate ligament injury: a two to nine-year follow-up study. Knee Surg Sports Traumatol Arthrosc 16(3):214–223
28. Moksnes H, Engebretsen L, Risberg MA (2012) The current evidence for treatment of ACL injuries in children is low: a systematic review. J Bone Joint Surg Am 94(12):1112–1119
29. Moksnes H, Engebretsen L, Risberg MA (2012) Management of anterior cruciate ligament injuries in skeletally immature individuals. J Orthop Sports Phys Ther 42(3):172–183
30. Moksnes H, Engebretsen L, Risberg MA (2013) Prevalence and incidence of new meniscus and cartilage injuries after a nonoperative treatment algorithm for ACL tears in skeletally immature children: a prospective MRI study. Am J Sports Med 41(8):1771–1779
31. Moksnes H, Engebretsen L, Seil R (2016) The ESSKA paediatric anterior cruciate ligament monitoring initiative. Knee Surg Sports Traumatol Arthrosc 24:680–687

32. Olsen OE, Myklebust G, Engebretsen L, Holme I, Bahr R (2005) Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. BMJ 330(7489):449
33. Reider B (2015) A matter of timing. Am J Sports Med 43(2):273–274
34. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, Georgoulis T, Hewett TE, Johnson R, Krosshaug T, Mandelbaum B, Micheli L, Myklebust G, Roos E, Roos H, Schamasch P, Shultz S, Werner S, Wojtys E, Engebretsen L (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412
35. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, Andersen TE (2008) Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. BMJ 337:a2469
36. Steffen K, Emery CA, Romiti M, Kang J, Bizzini M, Dvorak J, Finch CF, Meeuwisse WH (2013) High adherence to a neuromuscular injury prevention programme (FIFA 11+) improves functional balance and reduces injury risk in Canadian youth female football players: a cluster randomised trial. Br J Sports Med 47(12):794–802
37. Woods GW (2004) Delayed anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med 32(1):201–210

Anatomical and Technical Considerations for Pediatric ACL Reconstruction

8

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and Franck Chotel

8.1 Introduction

Pediatric (ACL) surgery is difficult and highly specialized due to the specific anatomy of children's knees and its serious complication potential. Therefore, anterior cruciate ligament replacement surgery in children is controversial [4, 12, 20, 53, 54, 56, 65, 66, 80], and many operative techniques have been described. Every surgical technique bears a specific risk for growth disturbances either through indirect growth changes in extraepiphyseal surgical procedures or through growth plate injuries in epiphyseal or transphyseal techniques [19, 34, 46, 52, 75]. Over the last decades, substantial surgical and experimental knowledge has been gained by several generations of surgeons to correctly estimate the risk of pediatric ACL reconstruction [72] in order to minimize the risk of growth abnormalities.

8.2 Anatomy and Function of the Growth Plate

The growth plate is located between the epiphysis and the metaphysis of long bones. It regulates endochondral growth and has in its center a complex anatomy with the following cellular layers (from the epiphyses to the metaphysis): the reserve zone, the proliferative zone, the layer with prehypertrophic chondrocytes, and the hypertrophic zone which is subdivided in cellular layers of maturation, degeneration, and calcification [30, 41]. Vascularization is separated between the epiphysis and the metaphysis, and as a consequence, the growth plate represents a frontier between these two structures playing an important role in the physeal pathology of certain tumors and infections. At its periphery we find the presence of the perichondral structures. They are composed of two structures (Fig. 8.1), the perichondral ring of LaCroix [37], which provides mechanical support, and the ossification groove of Ranvier [64] which provides cells for

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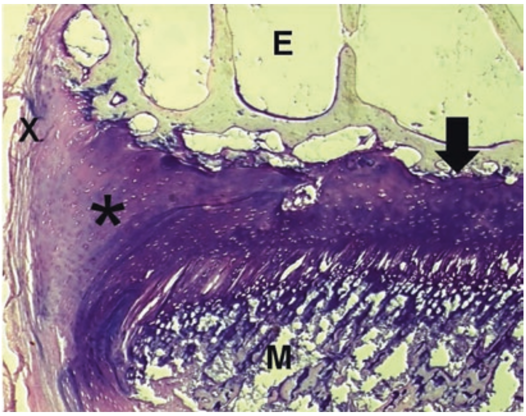

Fig. 8.1 Distal femoral growth plate of a 10-month-old sheep (*x* perichondral fibrous ring of LaCroix, *ossification groove of Ranvier, *E epiphysis*, *M* metaphysis, *arrow* center of the growth plate with columnar chondrocyte structure) (Giemsa staining; magnification × 25)

growth in width and which is a stem cell niche [31]. They have an important physiologic role, thus constituting the crossroads between longitudinal growth and growth in width of the bone. Furthermore, their presence plays an important role in the stabilization of this transitional zone between the epiphysis and the metaphysis. The perichondral structures do also play an important role from a pathologic point of view through the specific pediatric fractures classified as #6 in the Ogden classification system [60].

8.3 Experimental Principles of Surgery with Open Growth Plates

The question of remaining endochondral growth after growth plate injuries has been of great interest for orthopedic surgeons for more than 150 years [6, 61]. Based on the first clinical experiences with epiphysiodesis [7, 63] in the first half of the twentieth century, many experimental studies were published with the goal to develop treatments regulating longitudinal growth like temporary epiphysiodesis, epiphysiolysis capitis femoris, and their respective fixation principles [5, 9, 17, 18, 23–26, 42, 43, 58, 76]. With the development of ACL reconstruction techniques and the identification of the problem of ACL injuries in children, several specific surgical-experimental studies analyzing pediatric ACL replacements were published during the last three decades. They were conducted in rabbits, pigs, sheep, and dogs with open growth plates [13, 14, 22, 29, 47–50, 57, 62, 71, 77]. They allowed recognizing the risks related to specific surgical techniques and especially the fact that a technically correct anterior cruciate ligament surgery in a pediatric patient bears little risk of a clinically relevant secondary growth change. From these experimental studies on the growth plate as well as clinical experiences from the past, a certain number of surgical principles can be applied either directly or indirectly to ACL reconstruction with open growth plates. They have been recently summarized in a review article [72] and are represented in Table 8.1.

Table 8.1 Surgical-experimental principles of pediatric ACL reconstruction [72]

1.	Growth plate cartilage does generally not regenerate after a drill injury
2.	Leaving a transphyseal drill hole empty results in the formation of a bone bridge
3.	Small bone bridges may resolve spontaneously
4.	The formation of a bone bridge may be prevented by the transphyseal placement of a tendon graft
5.	Permanent transphyseal hardware placement can result in a growth abnormality
6.	A central growth plate lesion may result in a symmetric shortening, whereas a peripheral growth plate lesion may result in an axial deformity
7.	The critical size for a growth abnormality due to a central growth plate lesion is 7–9 % of the size of the growth plate
8.	The critical size for a growth abnormality due to a peripheral growth plate lesion is 3–5 % of the circumference of the growth plate
9.	The size of the growth plate injury increases with drilling obliquity
10.	The risk of a growth deformity is inversely proportional to the remaining growth potential
11.	The force of the growth plate is associated with body weight
12.	An excessive graft tension may lead to a tenoepiphysiodesis
13.	During femoral tunnel drilling, iatrogenic injury to perichondral structures should be avoided
14.	Epiphyseal and transphyseal ACL reconstructions may induce rotational deformities at the distal femur
15.	Graft incorporation is faster in immature specimen as compared to adults

8.4 Surgical Techniques

Many surgical techniques have been described in order to perform the best possible ACL replacement in children and at the same time to reduce the surgically induced complication potential to a minimum. On the contrary to an adult knee, an anatomic graft placement is difficult to obtain in children with the currently available techniques [45]. This is due to the presence of the growth plates, especially on the femoral side. According to the localization of the tibial and femoral tunnels, the surgical techniques can be divided into three categories (Fig. 8.2): (a) transphyseal procedures, where the tunnels are drilled through the growth plates; (b) epiphyseal techniques, where the tunnels are located in the tibial and femoral epiphyses, not injuring the growth plate; and (c) extraepiphyseal techniques, where the graft is placed around the growth plate. Finally, different types of graft placements can be used on the tibial side and the femoral side. Every surgical technique bears its own, specific complication potential. General surgical guidelines have been established to make the surgical procedure as safe as possible with respect to continuity of normal growth (Table 8.1).

The different graft types, which are used in adults, may also be used with some modifications in children. Hamstring grafts are probably the most popular. In some rare cases, they can be too thin and may be reinforced with other tendon material, i.e., by a quadriceps or iliotibial band strip. It is important not to harm the periosteal attachment of the hamstrings [72, 75]. As opposed to the adult harvesting technique, the tibial attachment site is left intact, and the hamstrings are cut proximal to their bony insertion site. This avoids an injury and potential growth arrest of the tibial tuberosity apophysis, which may cause a later development of a recurvatum knee. Quadriceps and patellar tendon grafts can be used as well, in which case they should be harvested without a bone block. If a bone block is part of the technique, care should be taken never to place it through the growth plate in order to avoid an early growth plate fusion. The iliotibial band may be used as a graft material as well, especially if an extraepiphyseal, extra-articular technique is performed [51]. Care should be taken to inform the patient on potential cosmetic (large incision) and harvesting site problems (pain). In Europe, there is limited experience with allografts in immature children. A new

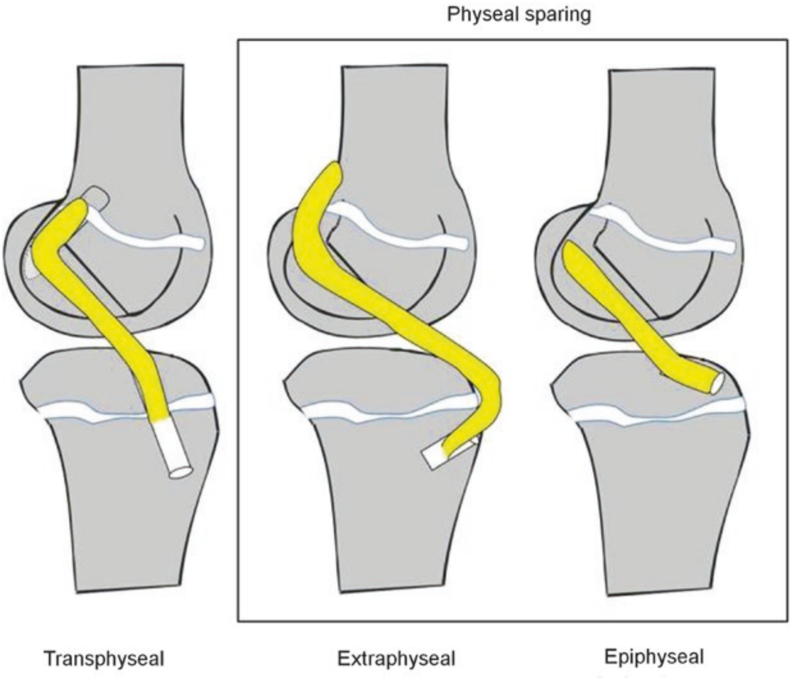

Fig. 8.2 Representation of different pediatric ACL reconstruction techniques in lateral knee views. Surgeons differentiate between transphyseal- and physeal-sparing techniques. The former implicate drilling of a bone tunnel through the femoral and tibial growth plates whereas the latter do not cause any direct iatrogenic physeal injuries, but bear the risk of indirect damage to the growth plate. ACL grafts are placed either within the epiphysis or around the physis. Many surgeons use different techniques on the femoral side and the tibial side

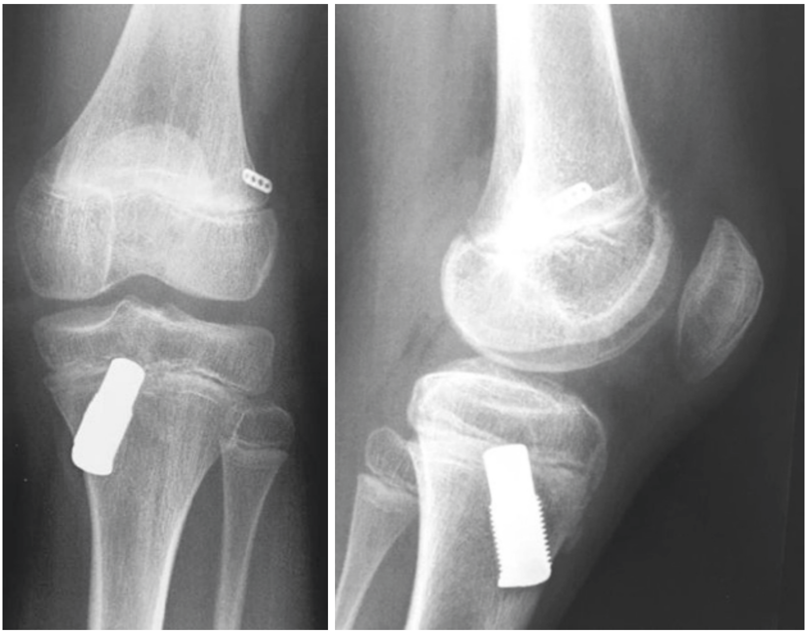

Fig. 8.3 Radiographs of a 12-year-old boy operated with an ACL repair technique. The boy developed a functional instability after surgery caused by insufficiency of the repair. The 10 mm metal monobloc containing a suture-tensioning device crossed the proximal tibial growth plate. The use of such implants must be critically evaluated before pediatric use in order to avoid large growth plate injuries and the need for extended revision surgery in case of failures

approach is the use of living donor hamstring tendon allografts. This allows for a more predictable graft size and for preservation of the child's own tendons for potential use in later life. First reports of parents donating their hamstring tendons to their children have recently been published and showed good results, both for the outcome of the child's and parent's knees [21]. The permanent use of synthetic graft material is prohibited as it may cause significant growth arrest as well as the need for complex, three-dimensional corrective surgeries for malalignment or leg length discrepancies. Newly developed ACL repair techniques [15] must be critically evaluated before pediatric use in order to avoid large growth plate injuries and the need for extended revision surgery in case of failures (Fig. 8.3).

Some authors differentiate their specific pediatric ACL reconstruction technique according to the amount of knee growth remaining [16]. In order to minimize the risk of growth disturbance, Kocher [33, 34] advocated a physeal-sparing combined intra-articular and extra-articular reconstruction with an autogenous iliotibial band in prepubescent (Tanner stage 1 or 2) children with a large amount of growth remaining. In pubescent adolescents with growth remaining (Tanner stage 3), they recommend a transphyseal hamstring graft technique with extracortical fixation [34]. This technique is similar to the one used by the first author of the present article on a routine basis, both in prepubescent children and adolescents [79] (Fig. 8.4). This arthroscopic single-bundle technique differs only minimally from the adult technique. Graft diameter generally varies between 6 and 8 mm. In prepubescent children under the age of 10, the femoral tunnel is drilled in a transtibial fashion. This allows for a more perpendicular positioning of the femoral tunnel in relation to the distal femoral physis in order to keep the drill injury as small as possible. After the age of 10 and with still significant knee growth remaining, the femoral tunnel is drilled through the anteromedial portal in deep knee flexion. This causes a larger drill injury but allows for a more anatomic femoral graft placement

Fig. 8.4 Radiographs of an ACL-reconstructed knee of an 11-year-old boy. *Left*: image shortly after surgery; *right*: 5 years after reconstruction and 20 cm of longitudinal growth. The clinical outcome was excellent: return to pivoting sport, Lachman and pivot shift tests were negative. The images illustrate anatomic changes after ACL reconstruction: (*1*) upward migration of the femoral tunnel, (*2*) verticalization of the femoral tunnel, (*3*) verticalization of Blumensaat's line, (*4*) relative thinning of the tibial tunnel, (*5*) and narrowing of the intercondylar notch

[72]. An injury of the perichondral structures should be avoided by all means [71]. Preventing a blowout of the posterior cortex can be achieved by using a femoral drill guide with a 5 or even a 7 mm offset. On the tibial side, care must be taken to position the tunnel entrance more medially as it is done in adults in order to protect the apophysis of the tibial tuberosity and avoid subsequent development of a varus knee and/or a recurvatum knee [74].

Anderson [1–3] uses a transphyseal technique with cortical fixation. The semitendinosus and gracilis tendons are harvested with a standard tendon stripper and detached distally. The tendons are prepared in a quadrupled manner with Endobutton for the femoral attachment. The femoral guidewire is drilled under fluoroscopic guidance in both antero-posterior (AP) and coronal plane with arthroscopic visualization of the intercondylar notch. The tibial guidewire is inserted to the anteromedial aspect of the tibia through the epiphysis with the aid of tibial drill guide. The graft is measured, and the smallest appropriate drill is used for the femoral and tibial tunnels to get a tight as possible fit. The graft is pulled to its place through the tunnels. A washer is placed to the femoral side to secure the Endobutton fixation. The tibial fixation is done in 10 degree knee flexion by tying the No. 2 FiberWire sutures over a tibial screw that is placed medial to the tibial tubercle apophysis and distal to the proximal tibial physis.

Chotel [10, 27] uses an arthroscopically assisted transphyseal technique on the tibial side and an intraepiphyseal technique on the femoral side (Fig. 8.5). The quadriceps tendon is harvested with a trapezoidal bone block from the patella. A femoral pin is inserted under fluoroscopic guidance in order to be parallel and at the same time at a safe distance from the physis. After validating the femoral pin placement, an outside-in technique is used for femoral tunnel drilling. The graft is introduced from outside-in and from the femur to the tibia. The bone block is impacted press-fit in the femoral tunnel. An extracortical staple and a biodegradable screw in the tunnel, which is placed distal to the tibial physis, achieve double tibial fixation.

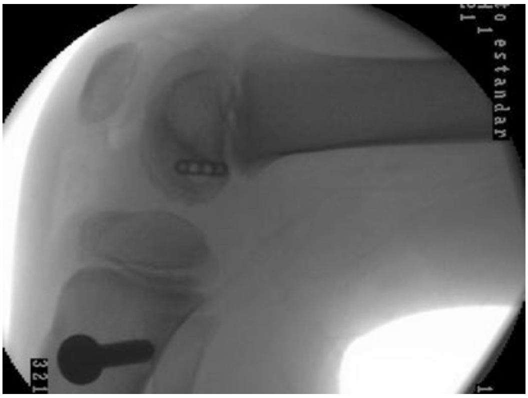

Fig. 8.5 Lateral fluoroscopic radiograph of a prepubescent child showing a femoral all-epiphyseal tunnel and graft fixation with Endobutton. The tunnel is parallel and distant of only a few millimeters to the growth plate. This technique requires a high precision and bears the risk of creating a larger growth plate injury as compared with a transphyseal technique (Courtesy of JC Monllau, MD, Barcelona, Spain)

An example of a nonanatomic, extraphyseal technique is the so-called Clocheville technique [8, 68] using the mid-third of the patella tendon without bone blocks. Instead of bone plugs, a periosteal flap is harvested at the patellar and the tibial insertion sites. The femoral tunnel is positioned proximally to the growth plate. On the tibial side, the graft is fastened at the epiphysis in a 1 cm deep bone trough. This procedure is technically more demanding than the arthroscopic single-tunnel technique. It has been used for many years, especially in very young, prepubertal children.

The tremendous evolution of arthroscopic ACL surgery has led to the recent development of an intraepiphyseal all-inside technique [44]. Both the femoral and tibial tunnels are drilled in a retrograde fashion and do not cross the physeal plate, hence allowing for a minimally invasive and anatomic reconstruction technique. It requires the intraoperative use of fluoroscopy in order to prevent physeal injuries. The soft tissue graft is deployed into the tunnels from the inside of the joint, and graft fixation is achieved over soft tissue fixation buttons. This technique is very promising but technically demanding. It can be considered to be in the pioneering phase of surgical development [73].

Rehabilitation is similar to all the techniques, although more carefully handled than in adults. There is no universally accepted rehabilitation protocol. Children are allowed to bear weight on the operated leg in an extension brace over a period of 6 weeks; motion must be started early on to avoid arthrofibrosis [59]; sports activities can be resumed after 6 months at the earliest, in many cases only after 9–12 months.

8.5 Risk of Growth Disturbances After ACL Surgery

The risks related to different techniques of pediatric ACL reconstruction are increasingly recognized, and scientific research in the field is growing. In the last decade, it has been shown that a technically correct pediatric ACL reconstruction has little risk in creating growth abnormalities [19]. Nevertheless, they do occur [11, 32, 35, 36, 67, Shifflett 2013], and the understanding of the pathophysiologic changes of an iatrogenic injury to the growing cartilaginous structures in the knee is still incomplete. Growth disturbances can be described from different perspectives, depending on their pathophysiological explanation, their anatomic location, and their clinical relevance. An attempt to classify these different aspects and the respective treatment options is presented in Table 8.2.

From a pathophysiological point of view, reported growth disturbances after ACL reconstruction were classified into three categories [11] (Fig. 8.6). The process of growth arrest (A) is caused by a localized growth plate injury, which generates the formation of a transphyseal bone bridge. Spontaneous breakage of the bone bridge may occur in very young children whose growth plate can create large distraction forces. Bone bridge formation can be prevented with a soft tissue graft at the height of the injured growth plate. A transphyseal bone block, i.e., with a quadriceps or a bone-patellar tendon-bone graft, a transphyseal hardware placement, or even a transphyseal synthetic ligament placement can cause such a sudden growth arrest as well. It is important for the surgeon to understand that a

Table 8.2 Classification criteria and treatment options of growth disturbances after ACL reconstruction

	Clinical presentation	Treatment option
Subtype	*Pathophysiological classification*	
A	Growth arrest	Early diagnosis: consider Langenskiöld procedure
		Late diagnosis: osteotomy
B	Acceleration of growth	Observation; eventually temporary epiphysiodesis
C	Growth deceleration	Consider ACL revision to release graft tension
Localization	*Anatomical classification* [11]	
Medial proximal tibia	Varus deformity	Uniplanar deformity correction if clinically relevant
Anterior tibial tuberosity	Recurvatum deformity	Uniplanar deformity correction if clinically relevant
Distal, posterolateral femur	Valgus deformity	Uniplanar deformity correction if clinically relevant
Distal femur and proximal tibia	Severe three-dimensional deformity	Complex, multiplanar deformity correction
Subtype	*Clinical classification*	
Clinical, symptomatic	≥5° deformity at end of growth	Deformity correction after end of knee growth
Clinical, asymptomatic	3–5° deformity at end of growth	Observation
Subclinical, asymptomatic	<3° deformity	Observation

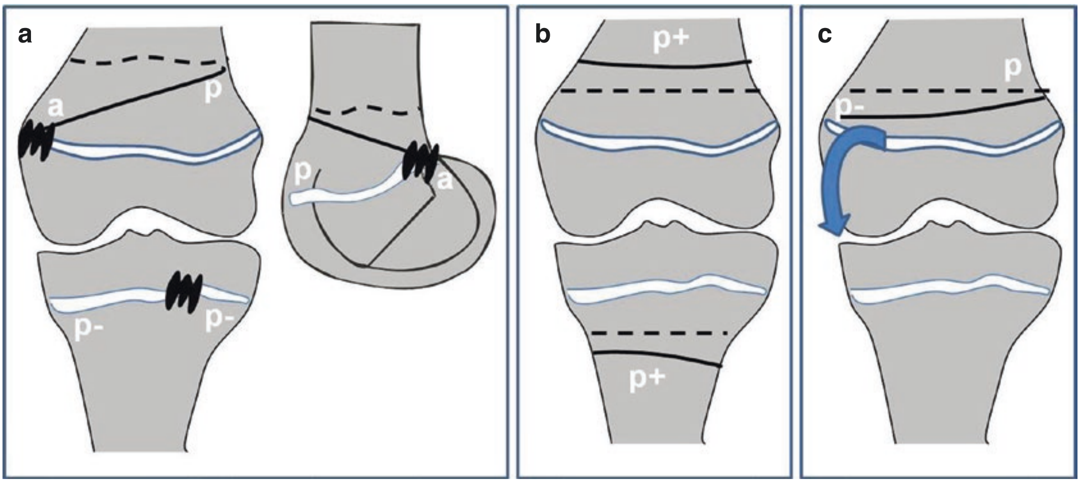

Fig. 8.6 Pathophysiological classification of growth disturbances after ACL reconstruction (Modified from [11]) (**a**) growth arrest is caused by a transphyseal bone bridge. (**b**) The second type of growth abnormality is an overgrowth process (type B: boost). (**c**) The 3D type of growth disturbance (type C: decelerate) may be caused by the so-called "tenoepiphysiodesis" effect

growth disturbance evolves throughout the remaining growth process. The amount of deformity is proportional to the localization and the size of the initial growth plate injury. A growth arrest can lead to axial deformities if it is located at the periphery of the physis or to symmetrical leg length discrepancies if it is located in the center of the growth plate. On the distal femur, peripheral growth plate injuries can be caused either by a tunnel with a too large diameter or a posterior blowout with an injury of the perichondral structures of the growth plate (Ranvier zone and perichondral ring of LaCroix) if a transphyseal technique is employed. If an epiphyseal tunnel is drilled (which should always be performed under fluoroscopy), the femoral tunnel is located distal to the growth plate. If a growth plate injury occurs with this technique, it will cause the development of a femoral valgus deformity. The growth disturbance will be much larger in comparison with the transphyseal technique, and asymmetric growth may be much more severe in comparison with an arrest would be caused by transphyseal drilling. Finally, if the surgeon chooses an extraepiphyseal technique (over the top technique), caution must be paid to avoid an excessive rasping of the over-the-top position for a better graft adherence. This surgical maneuver may injure the perichondral structures and lead to axial malalignment as well [71]. Due to its posterolateral position, a growth arrest at the femoral tunnel will lead to a deformity in valgus and flexion. In such cases, anticipating the remaining growth allows to predict the amount of deformity. On the tibial side, peripheral injuries may be caused by damaging the tibial tuberosity apophysis, either during harvesting of the hamstring tendons or through a too anterior positioning of the tibial tunnel entrance. In this case, the growth arrest will cause a recurvatum of the proximal tibia [75].

The second type of growth abnormality is an overgrowth process (type B: **b**oost). It may be caused by a local hypervascularization, which stimulates the physeal growth process. This growth disturbance is temporary, and it usually becomes apparent in a limited period of 2 years following surgery. It is usually symmetric in which case it leads to a leg length discrepancy. Sometimes, a tibial valgus deformity can also occur, due to asymmetrical overgrowth. This is similar to the valgus deformities observed after pediatric tibial diaphyseal fractures. In order to rule out a preoperatively existing leg length discrepancy, we recommend performing bilateral long-leg standing radiographs on a systematic basis. In this respect, it should be kept in mind that 77 % of the subjects in a general population have a leg length discrepancy of 7 mm or less [69]. Therefore, Frosch et al. [19] recommended considering leg length differences after pediatric ACL reconstruction only from 1 cm or more.

The 3D type of growth disturbance (type C: decelerate) may be caused by the so-called "teno-epiphysiodesis" effect [14, 62]. In this case, an excessive graft tension across the physis causes a deceleration of the remaining growth and a secondary growth abnormality. The exact amount of graft tension being able to cause such an abnormality in humans has not been defined yet. Experimental animal studies have shown that it should not exceed 80 N. The mechanism behind this growth abnormality is called the Hueter-Volkmann principle, according to early experimental studies, which showed that an excessive pressure on the growth plate reduced longitudinal growth and vice versa [28, 78].

The clinical relevance or in other words the threshold from which a deformity may become symptomatic is difficult to define. It depends on the anatomic localization as well as the plane (frontal vs. sagittal) and the amount of the deformity. In a previous study [70], it has been shown that axial deformities of 3° or less may be related to a measurement error. Although they would probably remain asymptomatic, malalignments from 3° upwards may become visible, whereas deformities of 5° or more may be considered clinically relevant and potentially detrimental in terms of compartment overload and long-term osteoarthritis development.

As a consequence of these possible growth abnormalities, children must undergo a much stricter postoperative follow-up as adults. Not performing this follow-up on a systematic basis may lead to an underestimation of growth abnormalities [55]. Clinical and radiological controls should therefore be mandatory until the end of the growth period. In case of a permanent growth abnormality, immediate surgical revision can be recommended if the cause of the complication has been clearly identified (i.e., transphyseal hardware or bone block placement). In such cases with a remaining growth potential, epiphyseal stapling or a Langenskiöld procedure may be considered [38–40]. If surgical revision is not considered immediately, a corrective osteotomy may be mandatory at the end of the growth period [35, 36, 67, 75]. In such cases, the complexity of the corrective procedure is strongly related to the complexity of the deformity where uniplanar single bone deformities are easier to correct than multiplanar malalignment concerning both the femur and tibia. Fortunately, these complications are extremely rare, especially if the surgical technique has been properly performed. Nevertheless, the children and their parents must be informed preoperatively that they may occur even in experienced hands.

References

1. Anderson AF (2003) Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. J Bone Joint Surg Am 85-A(7):1255–1263
2. Anderson AF (2004) Transphyseal replacement of the anterior cruciate ligament using quadruple hamstring grafts in skeletally immature patients. J Bone Joint Surg Am 1(Pt 2):201–209
3. Anderson AF, Anderson CN (2009) Transepiphyseal anterior cruciate ligament reconstruction in pediatric patients. Sports Health 1(1):76–80
4. Anderson AF, Anderson CN (2015) Correlation of meniscal and articular cartilage injuries in children and adolescents with timing of anterior cruciate ligament reconstruction. Am J Sports Med 43:275–281
5. Barash ES, Siffert RS (1966) The potential for growth of experimentally produced hemiepiphyses. J Bone Joint Surg Am 48:1548
6. Bidder A (1873) Experimente über die künstliche Hemmung des Längenwachstums von Röhrenknochen durch Reizung und Zerstörung des Epiphysenknorpels. Naunyn-Schmiedebergs Arch Exp Path Pharmak 1:248–263
7. Blount WP, Clarke GR (1949) Control of bone growth by epiphyseal stapling. Prelim Rep J Bone Joint Surg 31-A:464–478
8. Bonnard C, Fournier J, Babusiaux D, Planchenault M, Bergerault F, de Courtivron B (2011) Physeal-sparing reconstruction of anterior cruciate ligament tears in children: results of 57 cases using patellar tendon. J Bone Joint Surg Br 93:542–547
9. Campbell CJ, Grisolia A, Zanconato G (1959) The effects produced in the cartilaginous epiphyseal plate of immature dogs by experimental surgical traumata. J Bone Joint Surg 41-A:1212–1242
10. Chotel F (2004) Knee sprains in children and adolescents. In: Duparc J (ed) Conférences d'enseignement, vol 80. Elsevier, Paris, pp 209–240
11. Chotel F, Henry J, Seil R, Chouteau J, Moyen B, Bérard J (2010) Growth disturbances without growth arrest after ACL reconstruction in children. Knee Surg Sports Traumatol Arthrosc 18:1496–1500
12. Chotel F, Seil R (2013) Growth disturbances after transphyseal ACL reconstruction in skeletally immature patients: who is more at risk? Young child or adolescent? J Pediatr Orthop 33:585–586
13. Chudik S, Beasley L, Potter H, Wickiewicz T, Warren R, Rodeo S (2007) The influence of femoral technique for graft placement on anterior cruciate ligament reconstruction using a skeletally immature canine model with a rapidly growing physis. Arthroscopy 23:1309–1319
14. Edwards TB, Green CC, Baratta RV (2001) The effect of placing a tension graft across open growth plates. J Bone Joint Surg Am 83:725–734
15. Eggli S, Kohlhof H, Zumstein M, Henle P, Hartel M, Evangelopoulos DS, Bonel H, Kohl S (2015) Dynamic intraligamentary stabilization: novel technique for preserving the ruptured ACL. Knee Surg Sports Traumatol Arthrosc 23(4):1215–1221. doi:10.1007/s00167-014-2949-x, Epub 2014 Mar 21
16. Fabricant PD, Jones KJ, Delos D, Cordasco FA, Marx RG, Pearle AD, Warren RF, Green DW (2013) Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: a review of current concepts: AAOS exhibit selection. J Bone Joint Surg Am 95(5):e28. doi:10.2106/JBJS.L.00772
17. Ford LT, Key JA (1956) A study of experimental trauma to the distal femoral epiphysis in rabbits. J Bone Joint Surg 38-A:84–92
18. Friedenberg ZB (1957) Reaction of the epiphysis to partial surgical resection. J Bone Joint Surg Am 39:332–340
19. Frosch KH, Stengel D, Brodhun T, Stietencron I, Holsten D, Jung C, Reister D, Voigt C, Niemeyer P, Maier M, Hertel P, Jagodzinski M, Lill H (2010) Outcomes and risks of operative treatment of rupture of the anterior cruciate ligament in children and adolescents. Arthroscopy 26:1539–1550
20. Funahashi KM, Moksnes H, Maletis GB, Csintalan RP, Inacio MC, Funahashi TT (2014) Anterior cruciate ligament injuries in adolescents with open physis: effect of recurrent injury and surgical delay on meniscal and cartilage injuries. Am J Sports Med 42:1068–1073
21. Goddard M, Bowman N, Salmon LJ, Waller A, Roe JP, Pinczewski LA (2013) Endoscopic anterior cruciate ligament reconstruction in children using living donor hamstring tendon allografts. Am J Sports Med 41(3):567–574. doi:10.1177/0363546512473576, Epub 2013 Jan 31
22. Guzzanti V, Falciglia F, Gigante A, Fabbriciani C (1994) The effect of intra-articular ACL reconstruction on the growth plates of rabbits. J Bone Joint Surg Br 76:960–963
23. Haas SL (1945) The changes produced in the growing bone after injury to the epiphyseal cartilage plate. J Orthop Surg 1:67–99

24. Haas SL (1945) Retardation of bone growth by a wire loop. J Bone Joint Surg Am 27:25–36
25. Haas SL (1948) Mechanical retardation of bone growth. J Bone Joint Surg Am 30:506–512
26. Haas SL (1950) Restriction of bone growth by pins through the epiphyseal cartilaginous plate. J Bone Joint Surg Am 32:338
27. Henry J, Chotel F, Chouteau J, Fessy MH, Berard J, Moyen B (2009) Rupture of the anterior cruciate ligament in children: early reconstruction with open physes or delayed reconstruction to skeletal maturity? Knee Surg Sports Traumatol Arthrosc 17:748–755
28. Hueter C (1862) Anatomische Studien an den Extremitätengelenken Neugeborener und Erwachsener. Virchow's Arch 25:575–599
29. Janarv PM, Wikström B, Hirsch G (1998) The influence of transphyseal drilling and tendon grafting on bone growth: an experimental study in the rabbit. J Pediatr Orthop 18:149–154
30. Jouve JL, Mottet V, Cottalorda J, Frayssinet P, Bollini G (1998) Reimplantation of growth plate chondrocyte cultures in central growth plate defects: part I. Charact Cult J Pediatr Orthop B 7:167–173
31. Karlsson C, Thornemo M, Barreto Henriksson H, Lindahl A (2009) Identification of a stem cell niche in the zone of Ranvier within the knee joint. J Anat 215:355–363
32. Kocher MS, Saxon HS, Hovis WD, Hawkins RJ (2002) Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the herodicus society and the ACL study group. J Pediatr Orthop 22:452–457
33. Kocher MS, Garg S, Micheli LJ (2005) Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. J Bone Joint Surg Am 87:2371–2379
34. Kocher MS, Smith JT, Zoric BJ, Lee B, Micheli LJ (2007) Transphyseal anterior cruciate ligament reconstruction in skeletally immature pubescent adolescents. J Bone Joint Surg Am 89:2632–2639
35. Koman JD, Sanders JO (1999) Valgus deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. A Case Rep J Bone Joint Surg Am 81:711–715
36. Kurosaka M (2013) Dramatic growth abnormality after paediatric ACL reconstruction with transphyseal synthetic graft placement. Instructional course, ISAKOS meeting, Toronto
37. Lacroix P (1951) The organization of bone. Churchill, London, pp 131–133
38. Langenskiöld A (1993) Partial closure of the epiphyseal plate. Principles of treatment. 1978. Clin Orthop Relat Res 297:4–6
39. Langenskiöld A, Videman T, Nevalainen T (1986) The fate of fat transplants in operations for partial closure of the growth plate. Clinical examples and an experimental study. J Bone Joint Surg Br 68:234–238
40. Langenskiöld A (1975) An operation for partial closure of an epiphysial plate in children, and its experimental basis. J Bone Joint Surg Br 57:325–330
41. Mackie EJ, Tatarczuch L, Mirams M (2011) The skeleton: a multi-functional complex organ. The growth plate chondrocyte and endochondral ossification. J Endocrinol 211:109–121
42. Mäkelä EA, Vainionpää S, Vihtonen K, Mero M, Laiho J, Tormala P, Rokkanen P (1987) The effect of a penetrating biodegradable implant on the epiphyseal plate: an experimental study on growing rabbits with special regard to polyglactin 910. J Pediatr Orthop 7:415–420
43. Mäkelä EA, Vainionpää S, Vihtonen K, Mero M, Helevirta P, Törmälä P, Rokkanen P (1989) The effect of a penetrating biodegradable implant on the growth plate. An experimental study on growing rabbits with special reference to polydioxanone. Clin Orthop Relat Res 241:300–308
44. McCarthy MM, Graziano J, Green DW, Cordasco FA (2012) All-epiphyseal, all-inside anterior cruciate ligament reconstruction technique for skeletally immature patients. Arthrosc Tech 1(2):e231–e239. doi:10.1016/j.eats.2012.08.005, Print 2012 Dec
45. McCarthy MM, Tucker S, Nguyen JT, Green DW, Imhauser CW, Cordasco FA (2013) Contact stress and kinematic analysis of all-epiphyseal and over-the-top pediatric reconstruction techniques for the anterior cruciate ligament. Am J Sports Med 41:1330–1339
46. McConkey MO, Bonasia DE, Amendola A (2011) Pediatric anterior cruciate ligament reconstruction. Curr Rev Musculoskelet Med 4:37–44
47. Meller R, Brandes G, Drögemüller C, Fritz F, Schiborra F, Fehr M, Hankemeier S, Krettek C, Hurschler C (2009) Graft remodeling during growth following anterior cruciate ligament reconstruction in skeletally immature sheep. Arch Orthop Trauma Surg 129:1037–1046
48. Meller R, Haasper C, Westhoff J, Brand J, Knobloch K, Hankemeier S, Hesse E, Krettek C, Jagodzinski M (2009) An animal model to study ACL reconstruction during growth. Technol Health Care 17:403–410
49. Meller R, Willbold E, Hesse E, Dreymann B, Fehr M, Haasper C, Hurschler C, Krettek C, Witte F (2008) Histologic and biomechanical analysis of anterior cruciate ligament graft to bone healing in skeletally immature sheep. Arthroscopy 24:1221–1231
50. Meller R, Kendoff D, Hankemeier S, Jagodzinski M, Grotz M, Knobloch K, Krettek C (2008) Hindlimb growth after a transphyseal reconstruction of the anterior cruciate ligament: a study in skeletally immature sheep with wide-open physes. Am J Sports Med 36:2437–2443
51. Micheli LJ, Rask B, Gerberg L (1999) Anterior cruciate ligament reconstruction in patients who are prepubescent. Clin Orthop Relat Res 364:40–47
52. Mohtadi N, Grant J (2006) Managing anterior cruciate ligament deficiency in the skeletally immature individual: a systematic review of the literature. Clin J Sport Med 16:457–464
53. Moksnes H, Engebretsen L, Risberg MA (2012) The current evidence for treatment of ACL injuries in children is low: a systematic review. J Bone Joint Surg Am 20(94):1112–1119. doi:10.2106/JBJS.K.00960

54. Moksnes H, Engebretsen L, Risberg MA (2013) Prevalence and incidence of new meniscus and cartilage injuries after a nonoperative treatment algorithm for ACL tears in skeletally immature children: a prospective MRI study. Am J Sports Med 41:1771–1779
55. Moksnes H, Engebretsen L (2015) It takes more than timing: letter to the editor. Am J Sports Med 43:NP14–NP15. doi:10.1177/0363546515585289
56. Moksnes H, Engebretsen L, Seil R (2015) The ESSKA paediatric anterior cruciate ligament monitoring initiative. Knee Surg Sports Traumatol Arthrosc. 7 Aug. [Epub ahead of print]
57. Murray MM, Magarian EM, Harrison SL, Mastrangelo AN, Zurakowski D, Fleming BC (2010) The effect of skeletal maturity on functional healing of the anterior cruciate ligament. J Bone Joint Surg Am 1(92):2039–2049
58. Nordentoft EL (1969) Experimental epiphyseal injuries: grading of traumas and attempts at treating traumatic epiphyseal arrest in animals. Acta Orthop Scand 40:176–192
59. Nwachukwu BU, McFeely ED, Nasreddine A, Udall JH, Finlayson C, Shearer DW, Micheli LJ, Kocher MS (2011) Arthrofibrosis after anterior cruciate ligament reconstruction in children and adolescents. J Pediatr Orthop 31:811–817
60. Ogden JA (1981) Injury to the growth mechanisms of the immature skeleton. Skeletal Radiol 6:237–253
61. Ollier L (1867) Traité expérimental et clinique de la régénération des os et de la production artificielle du tissu osseux, vol 1 und 2. Masson, Paris
62. Ono T, Wada Y, Takahashi K, Tsuchida T, Minamide M, Moriya H (1998) Tibial deformities and failures of anterior cruciate ligament reconstruction in immature rabbits. J Orthop Sci 3:150–155
63. Phemister DB (1933) Operative arrestment of longitudinal growth in the treatment of deformities. J Bone Joint Surg 15:1–15
64. Ranvier L (1889) Traité technique d'histologie, 2nd edn. Savy, Paris, pp 356–7
65. Reider B (2015) A matter of timing. Am J Sports Med 43:273
66. Reider B (2015) It takes more than timing: response. Am J Sports Med 43:NP15–NP16. doi:10.1177/0363546515585290
67. Robert HE, Casin C (2010) Valgus and flexion deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. Knee Surg Sports Traumatol Arthrosc 18:1369–1373
68. Robert H, Bonnard C (1999) The possibilities of using the patellar tendon in the treatment of anterior cruciate ligament tears in children. Arthroscopy 15:73–76
69. Rush WA, Steiner HA (1946) A study of lower extremity length inequality. Am J Roentgenol Radium Ther 56:616–623
70. Seil R, Robert H (2005) VKB-Plastik bei offenen Wachstumsfugen. Arthroskopie 18:48–52
71. Seil R, Pape D, Kohn D (2008) The risk of growth changes during transphyseal drilling in sheep with open physes. Arthroscopy 24:824–833
72. Seil R, Weitz F, Pape D (2015) Surgical-experimental principles of anterior cruciate ligament (ACL) reconstruction with open growth plates. J Exp Orthop 2:11
73. Seil R, van Heerwaarden R, Lobenhoffer P, Kohn D (2013) The rapid evolution of knee osteotomies. Knee Surg Sports Traumatol Arthrosc 21:1–2. doi:10.1007/s00167-012-2175-3
74. Shea KG, Appel PJ, Pfeiffer RP (2003) Anterior cruciate ligament injury in paediatric and adolescent patients. Sports Med 33:455–471
75. Shifflett GD, Green DW, Widmann RF, Marx RG (2015) Growth arrest following ACL reconstruction with hamstring autograft in skeletally immature patients: a review of 4 cases. J Pediatr Orthop [Epub ahead of print]
76. Siffert RS (1956) The effect of staples and longitudinal wires on epiphyseal growth. An experimental study. J Bone Joint Surg Am 38:1077
77. Stadelmaier DM, Arnoczky SP, Dodds J, Ross H (1995) The effect of drilling and soft tissue grafting across open growth plates. Am J Sports Med 23: 431–435
78. Volkmann R (1862) Chirurgische Erfahrungen über Knochenverbiegungen und Knochenwachstum. Arch Pathol Anat 24:512–540
79. Wilmes P, Lorbach O, Chotel F, Seil R (2009) Ersatzplastik des vorderen Kreuzbandes bei offenen Wachstumsfugen. Arthroskopie 22:35–44
80. Yoo WJ, Kocher MS, Micheli LJ (2011) Growth plate disturbance after transphyseal reconstruction of the anterior cruciate ligament in skeletally immature adolescent patients: an MR imaging study. J Pediatr Orthop 31:691–696

Analgesia for Anterior Cruciate Ligament Reconstruction

9

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9.1 Introduction

Anterior cruciate ligament reconstruction (ACLR) is one of the most frequently performed ambulatory orthopedic procedures in the United States and Europe, increasing by 50 % from 1994 to 2006 in the United States [46]. While knee arthroscopy is frequently accompanied by only minor pain, ACLR involves more significant incisions in the vicinity of the joint, as well as drilling, tunneling, and anchoring in bone, and in some patients, harvesting native tendons for autografts, all of which may contribute to substantially more postoperative pain for the patient. Because ACLR is usually conducted on an ambulatory basis, effective analgesia is imperative. In a recent multicenter study of postoperative pain related to many surgical types conducted in Germany, Gerbershagen et al. noted that ACLR is accompanied by moderate-to-severe levels of pain [21]. Standard regimens of intraoperative and postoperative opioids are insufficient in many ways, given the side effects and adverse effects that accompany these drugs. Further, the use of exclusively opioids for pain management is likely to result in a higher frequency of unexpected admissions and longer periods in the recovery area, compared to administration of multimodal techniques inclusive of regional anesthesia [73]. In this chapter we consider different ways of managing the pain of ACLR and the evidence that supports these therapeutic regimens.

9.2 Importance of Effective Pain Management

Providing effective analgesia for complex and painful orthopedic surgeries has many potential benefits. Patient satisfaction is increased as pain management is improved, especially if opioid side effects, such as dizziness and nausea, are reduced [24, 25]. In both inpatient and outpatient settings, effective pain control may allow for earlier patient discharge [11, 25]. Effective pain control allows participation in surgeon-specified exercises at home and during physical therapy, with improved passive range of motion noted in studies that have evaluated this outcome [30]. Patients who are relatively comfortable, with

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minimal opioid requirements, are also able to ambulate sooner [24, 69] and have less disturbance of sleep patterns in the days after surgery [29]. Furthermore, unwillingness to move a painful extremity may lead to increased edema, arthrofibrosis, deep venous thrombosis, rehospitalization, and additional surgical procedures to address some of these issues.

9.3 Relevant Innervation of the Knee

The innervation of the knee is provided by the femoral, sciatic, and obturator nerves [15]. As described by Horner and Dellon, the medial femoral cutaneous branch of the femoral nerve provides innervation to the medial aspect of the joint and the prepatellar plexus [27]. The saphenous branch of the femoral nerve innervates the anterior and inferior knee capsule, as well as the cutaneous structures inferior and medial to the patella. In addition, the branches of the femoral nerve to the vastus medialis, vastus lateralis, and vastus intermedius provide branches that innervate the knee joint capsule [19, 27] (Fig. 9.1). In some patients, the obturator nerve has been shown to provide a contribution to the subsartorial plexus, which contributes to knee joint innervation. The lateral aspect of the joint is innervated by branches from the common peroneal and from the superior lateral genicular nerve, which branches from the sciatic nerve superior to the joint. In the posterior portion of the capsule, innervation is provided by both the posterior branch of the obturator nerve and the posterior articular branches of the tibial nerve. Arthroscopically assisted ACL reconstruction is most likely to involve the anterior and medial joint for the insertion of arthroscopic ports, the distal patellar and infero-patellar region for cutaneous incisions, and the proximal-medial portion of the anterior tibia as well as the intercondylar region of the femur, where tunnels are drilled in order to anchor the graft [28, 51]. Additional incisions and dissection for harvesting will vary with the graft type used for the reconstruction.

These areas of incision, dissection, and osseous manipulation suggest that in many patients, not only the femoral nerve but also the sciatic nerve provides innervation to the tissues affected by ACL reconstruction. In particular, when the semitendinosus and gracilis tendons are harvested for autograft, posterior pain in the sciatic distribution is expected; a sciatic nerve block logically may be utilized to assist with postoperative analgesia [72]. However, when allograft or anterior sources of autograft (patellar or quadriceps tendon) are utilized, the utility of sciatic nerve blockade may be of less importance. Nonetheless, peripheral blockade affecting only the femoral nerve and its branches may leave some of these patients with poorly controlled pain, particularly inferior to the knee joint or deep within the joint. In an anatomic study of the anterior knee capsule in adult cadavers, Franco et al. noted that the inferolateral branch of the common peroneal nerve and the lateral articular branch from this nerve both provide sensory innervation to the anterior knee capsule [19]. In addition, drilling through the proximal tibia and deep into the femoral condyles may affect the boney innervation provided by the sciatic nerve.

9.4 Therapeutic Options for Analgesia After ACLR

As noted above, a purely opioid-based regimen has many drawbacks. However, non-opioid analgesics may be utilized in concert with opioids in multimodal pharmacologic schemes to take advantage of multiple different pain control pathways. In addition, regional anesthesia techniques, both peripheral and neuraxial, may be employed with pharmacotherapeutic agents to good effect. The option to utilize continuous catheter techniques will be discussed below.

9.4.1 Opioids and Their Adverse Effects

Postoperative nausea and vomiting (PONV) is perhaps the most familiar and prevalent adverse

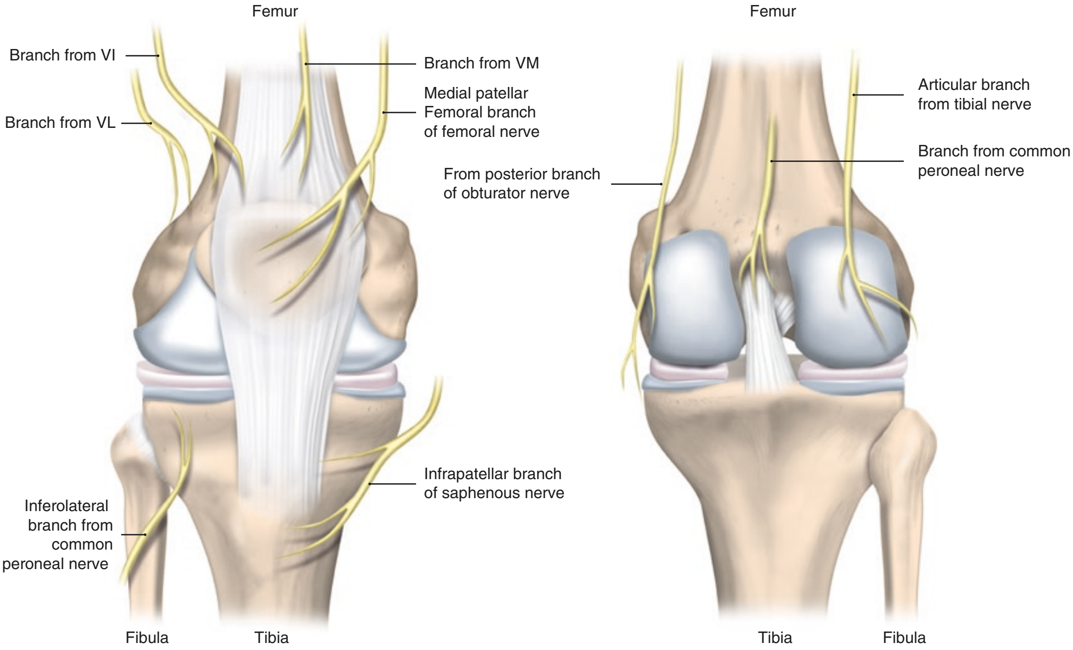

Fig. 9.1 Schematic of innervation of the periarticular region and joint capsule of the knee [Refs. formerly 11, 12]

effect of these drugs in the perioperative period. Over 50 % of patients who receive no prophylaxis in the high-risk setting will develop this symptom [4]. Risk factors include female gender, a history of prior PONV, motion sickness, nonsmoking status, and use of postoperative opioids [64]. PONV may be responsible for delayed discharge from the recovery area, prolonged hospital stay, and unexpected hospital admission with attendant economic consequences [64, 73]. Restricting the administration of opioid, through the use of multimodal analgesia and/or peripheral nerve blockade, reduces PONV, reduces unexpected delays in discharge, and improves patient satisfaction [24, 59, 73].

Examples of other common and frustrating clinical side effects of opioids include constipation, nausea, pruritus, dysphoria, and urinary retention [20, 70]. More serious adverse effects that may occur include ileus, with attendant delays in oral intake, as well as oversedation and life-threatening hypoventilation [45]. Many deaths have been attributed to treatment of both acute and chronic pain with opioids [10]. Importantly, there is a considerable amount of literature that describes not only tolerance to opioids from chronic use but also rapid acute tolerance to perioperative opioids [3, 37, 41, 48]. Lastly, the use of these agents may contribute to opioid-induced hyperalgesia in the acute postoperative pain setting [57].

9.4.2 Multimodal Analgesia

A multimodal treatment plan is of particular benefit in the management of patients' perioperative pain, given the inherent limitations of opioids. Multimodal analgesia incorporates various pharmacological agents such as acetaminophen, nonsteroidal anti-inflammatories, gabapentinoids, and α-2 agonists [34, 77], as well as non-pharmacologic techniques (Tables 9.1). Both acetaminophen (administered orally or intravenously) and nonsteroidal anti-inflammatory agents have been shown to significantly reduce postoperative opioid requirements in painful surgical procedures. Additionally, gabapentinoids are frequently utilized for their contribution to postoperative analgesia but may cause dizziness and sedation [77]. The preoperative use of both beta-blockers and alpha-2 agonists has been shown to have anesthetic-sparing and analgesic-sparing effects and reduce postoperative pain while potentially improving cardiovascular stability [71]. In addition, steroids, local anesthetic systemic infusions, and magnesium have all shown some promise in the management of acute pain [14, 29]. Recent interest in the use of agents providing multimodal analgesia to reduce the potential for chronic postsurgical (incision-related) pain remains speculative [68].

9.4.3 Regional Anesthesia Techniques

9.4.3.1 Neuraxial Blockade

Neuraxial anesthesia, either spinal or epidural, may be utilized for ACL reconstruction surgery, although the duration of action in these ambulatory procedures is necessarily limited to the period of surgical intervention, in contrast to procedures carried out in the inpatient setting, for which long-acting opioids may be added or an epidural catheter may be utilized for 24 h (or longer) of pain relief. These central blocks allow for rapid onset, minimal patient discomfort during the procedures, and improved immediate postoperative pain relief [52]. Avoiding general anesthesia for simple and complex knee procedures by utilizing neuraxial blockade and incorporating peripheral nerve blockade for the more painful surgeries has been shown to reduce postoperative pain and nausea and reduce unexpected admission [74].

Table 9.1 Pharmacologic agents utilized in multimodal analgesia

Gabapentanoids
Acetaminophen
Nonsteroidal anti-inflammatory agents
Celecoxib
Opioids
Systemic local anesthetic infusions
Magnesium
Steroids
NMDA receptor antagonists (e.g., ketamine)
Alpha-2 agonist agents (e.g., dexmedetomidine)

Most data related to subarachnoid block (spinal block) and ambulatory knee surgery are derived from studies of knee arthroscopy. In general, these have demonstrated that the subarachnoid block provided superior immediate postoperative pain control, reduced requirements for opioids in the early postoperative phase, a higher ability to “bypass” the PACU, and lower rates of postoperative nausea and vomiting (PONV) [33, 38] in comparison to the use of general anesthesia. However, a meta-analysis [42] did not support lower PONV rates for spinal anesthetics. Most of these studies did not reveal earlier discharge from the hospital with spinal block, despite the noted advantages. However, lower-dose spinals, particularly when utilized in a “unilateral” application (which can be accomplished by placing patients in lateral position during block administration), do allow for more rapid resolution and earlier ambulation [54] than conventional doses, especially when they affect both legs. Inclusion of opioids, such as fentanyl, in the spinal block allows for lower doses and faster return of function [55], but this may come at the cost of side effects such as nausea and pruritus [54]. In addition, when compared to peripheral nerve blockade, such as femoral and sciatic nerve blocks, spinal anesthesia may result in prolonged times to urination and recovery of ambulation, adversely affecting discharge times for ambulatory procedures [13].

In 2003, Williams et al. summarized the experience at a major university hospital’s sports orthopedics program, over a 4-year period, accounting for 1,200 ambulatory knee procedures [72]. In this observational study, the authors evaluated the experience of patients for whom a specified perioperative management pathway, incorporating neuraxial anesthesia and/or peripheral nerve blocks of various types, had been utilized, for simple knee arthroscopy or one of six complex procedures. Patients undergoing the complex procedures were more at risk for pain and benefitted to a greater degree from the use of either neuraxial anesthesia or peripheral nerve blockade, with better control of pain and a markedly decreased risk of unexpected hospital admission, when compared to similar patients who did not receive blocks.

In summary, subarachnoid block as a primary anesthetic technique has been well studied in ambulatory knee procedures and offers potential advantages over standardized general anesthetic techniques, including improved early pain control, reduced PONV (in some studies), and improved ability to bypass the PACU, all of which may have a favorable impact on patient satisfaction. However, there is less literature available comparing this type of neuraxial anesthetic to general anesthesia when optimized with multimodal analgesia and complementary peripheral nerve blockade for postoperative analgesia.

9.4.3.2 Peripheral Nerve Blockade: Single-Injection Approaches

Regional anesthesia has many potential benefits and should be considered as a component of a multimodal treatment plan for the ACLR patient, in order to minimize the side effect burden of opioid medications (Tables 9.2). Peripheral nerve blockade is practical and effective for pain control in the perioperative setting, for orthopedic procedures and other painful surgeries [22, 61]. In a meta-analysis, Liu et al. found that both neuraxial and peripheral nerve blockade reduced postoperative pain scores and reduced PACU analgesic administration compared to general anesthesia [42]. However, in this analysis, only peripheral blocks reduced postoperative nausea and vomiting.

Peripheral nerve block (PNB) techniques have been shown to be quite efficacious in controlling the pain of ACL reconstruction. In general, PNB offers a variety of desirable effects in ambulatory orthopedic surgery. These include reduced pain scores in the immediate aftermath of surgery, reduced opioid use as well as reduced side effects from opioids (such as nausea and dizziness), diminished time in the postanesthesia care unit (PACU), higher likelihood of bypassing the PACU completely, and earlier discharge from the hospital [24, 25, 49]. Patient satisfaction is also improved [24, 25], in comparison to the use of general anesthesia without PNB. In addition, patients are able to take oral fluid and food and walk sooner than with general anesthesia alone, and patient satisfaction scores are increased [24].

For ACLR, femoral nerve block is most commonly employed (Fig. 9.1a, b). As noted above, the femoral nerve provides capsular innervation to the knee, as well as innervation of the skin over the patella, the medial aspect of the knee (in some patients), and the infrapatellar region, via the saphenous nerve's infrapatellar branch [15]. In 2006, Williams et al. conducted a randomized, controlled trial of single injection and continuous PNB compared to multimodal pharmacologic analgesic techniques, utilizing intraoperative ketamine with postoperative oral immediate- and gradual-release opioids as well as nonsteroidal anti-inflammatory agents [75]. Both of the PNB groups reported lower pain scores than the control group at 24 h after surgery, and there were no functional sequelae at the 6-month postoperative evaluation. In a comprehensive review, Stein et al. noted the reported benefits of FNB in ACLR as improved early postoperative pain control, reduced use of opioids, and fewer opioid side effects [65].

Other studies have shown substantial improvements in pain control with femoral nerve block in ACLR as well. Wulf et al. evaluated several different types and concentrations of local anesthetics for analgesia in ACLR. Compared to placebo, all of the FNB groups had significantly lower pain scores and opioid requirements in the immediate postoperative period, up to 4 h [76]. In a retrospective review of 376 pediatric cases of ACLR, in which 35 % of patients had received femoral block, Schloss et al. reported a reduction in postoperative pain scores, lower opioid requirements, a shorter hospital stay, and reduced admission rate in those who had received the nerve blocks [60]. Williams et al. in an assessment of the impact of a perioperative analgesia pathway in 1,200 patients undergoing ambulatory knee surgery reported better pain control, reduced opioid use, and earlier discharge from the PACU in those with complex procedures (including ACLR) when nerve blocks were included in the anesthetic management [72]. In a later observational study of 948 patients undergo-

Table 9.2 Nerve block techniques for ACLR

Location/block	Advantages	Disadvantages
Femoral nerve block (FNB)	Excellent analgesia	Potential quadriceps atrophy
	Nerve readily visualized with US	Leg weakness/fall risk
Sciatic nerve block	Useful for posterior/lateral/inferior pain to supplement FNB	Leg weakness/fall risk
Adductor canal block (ACB)	Minimal quadriceps effect	Nerve less visible than FNB
		Less analgesia than FNB
Local anesthetic infiltration	Simple to perform	Less profound analgesia
By surgeon	No motor effects	

ing ACL reconstruction, Williams et al. reported that the use of femoral and sciatic nerve blocks was associated with a markedly reduced requirement for admissions to the phase I recovery (vs. direct admission to phase II recovery) and also a more than 75 % reduction in unexpected hospital admission, with an attendant drop in hospital costs of 12 % [73]. Other trials evaluating the impact of femoral nerve block in ACLR have resulted in similar findings [31, 53].

Adductor canal block (ACB) (Fig. 9.2a, b) has taken on increasing importance and popularity as a means of providing analgesia in total knee arthroplasty (TKA), with minimal or no quadriceps weakness, thus allowing earlier participation in rehabilitation [32], with a lower likelihood of falls [23]. In an early assessment of the use of ACB, this block did not appear to be as effective for analgesia for ACLR as it has for TKA [16]. However, in a more recent evaluation of ACB for ACLR, Espelund et al. found that pain was significantly better controlled compared to the use of general anesthesia, with sparing of quadriceps strength compared to the group which received a block of the femoral nerve [17].

More distal approaches to saphenous nerve branches have been utilized in an attempt to provide analgesia while sparing quadriceps function. Lundblad et al. in a randomized trial of 64 patients compared a standard multimodal regimen to infrapatellar nerve block, provided just above the level at which the saphenous nerve divides [43]. Compared to a sham block, this reduced pain significantly at 16–24 h (as the medications provided for multimodal analgesia were resolving) and improved the ability of patients to sleep in the first postoperative night.

Fig. 9.2 (**a**) Use of ultrasound guidance to perform femoral nerve block. (**b**) Ultrasound image of needle adjacent to femoral nerve, before injection of local anesthetic

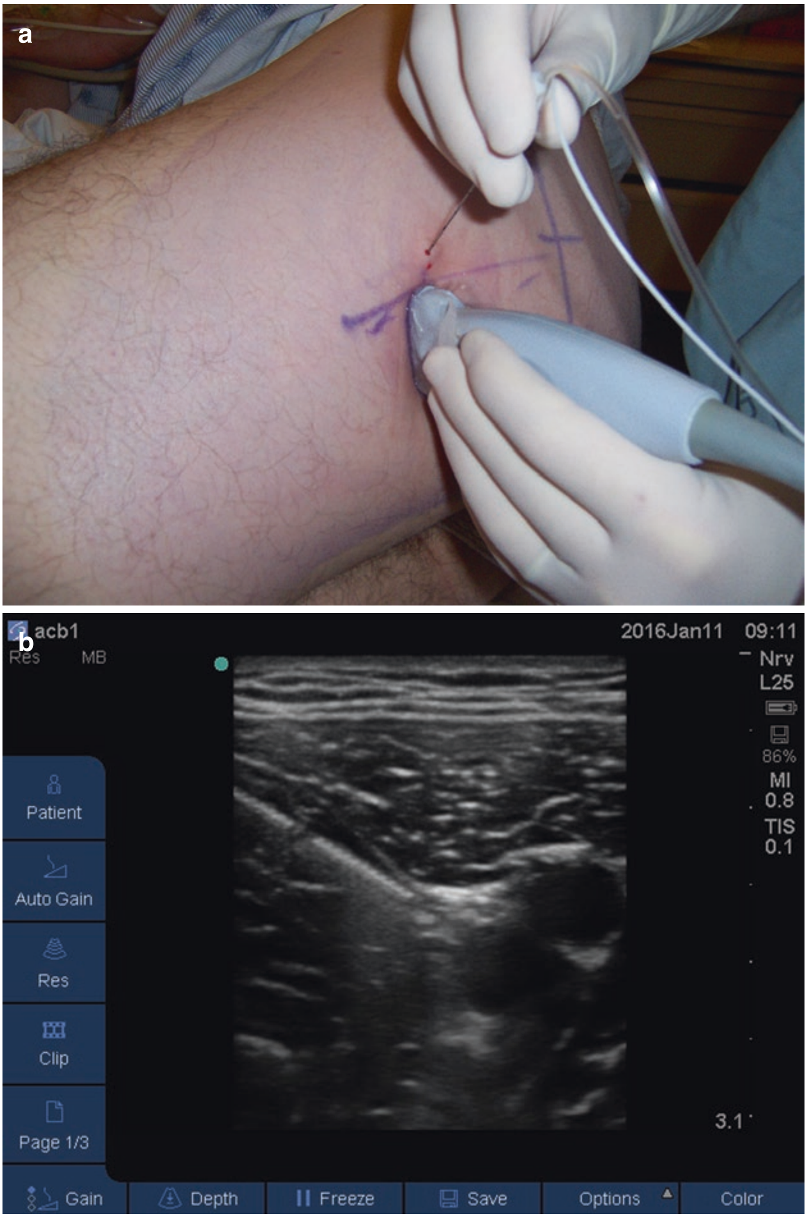

Fig. 9.3 (**a**) Use of ultrasound guidance to perform sciatic nerve block. (**b**) Ultrasound image of needle adjacent to sciatic nerve, before injection of local anesthetic

When the semitendinosus tendon is utilized as an autograft for ACLR, femoral nerve blockade will not provide analgesia to the region of the harvest. This may be addressed with pharmacologic methods, or with sciatic nerve blockade, either proximally, in the gluteal region, or distally, in the proximal popliteal fossa (Fig. 9.3a, b) [1]. In many regional anesthesia-oriented practices, a supplement sciatic block is provided routinely for this situation [72]. In addition, drilling and tunneling through the proximal tibia for ACLR occur in an area in which the sciatic nerve may also play a role in innervation and postoperative pain. Finally, as noted above, the anterior capsule of the knee receives significant innervation in its inferior and lateral aspects from the common peroneal nerve [19]. For all of these reasons, sciatic nerve block may be necessary to complement FNB, even when the ACLR utilized allograft or patellar- or quadriceps-tendon autograft. Hibbard et al. evaluated 50 such patients in a prospective, observational trial and found that in 20 % of cases, patients complained of moderate-to-severe postoperative pain in PACU, despite a functioning femoral nerve block and multiple doses of postoperative opioids; all of these patients received rapid relief from a supplemental postoperative sciatic nerve block [26].

Some orthopedists have attempted to address the posterior pain of hamstring harvest more directly. Bushnell et al. conducted a comparative trial of injection of bupivacaine 0.25 % into the hamstring donor site, as compared to no injection, in which all patients received preoperative femoral nerve block [8]. Visual analog pain scores were 2–3.5 units higher in those without block during the immediate postoperative period. Likewise, Fauno et al. found that a directed hamstring injection of local anesthetic provided superior pain control in the PACU and immediate postoperative period [18].

While the obturator nerve is known to innervate the knee joint capsule and often innervates the skin over the medial aspect of the joint [15], its role in pain of ACLR is less certain. There are no comparative trials exploring the utility of the obturator nerve block in this setting. Anecdotally, a rare patient with refractory medial pain after ACLR may obtain relief when an obturator nerve block is provided as a “rescue” in the postoperative phase. Obturator block may be most effectively conducted in the proximal thigh [67] or with a posterior “lumbar plexus block” in the low lumbar region [36]; attempts to block this nerve as part of a multicomponent “three in one” block at the groin, with high volumes of local anesthetic solution, are considerably less successful.

The guidance technique by which PNB is carried out, for femoral and sciatic blocks, has gradually transitioned in North America from the use of peripheral nerve stimulation (PNS) to ultrasound (US) over the past 10 years. In prior decades, PNS offered both relative accuracy and a high degree of safety [5, 7]; however, US guidance offers many additional benefits. These include ability to image the anatomy at bedside and to plan the safest and most direct route of needle placement, reducing the likelihood of encountering a blood vessel [47]. While this is but a “surrogate” marker for intravascular injection, the use of US guidance has clearly been shown to reduce the likelihood of intravascular injection with local anesthetic systemic toxicity, which may be a life-threatening occurrence [6, 56, 63]. US guidance allows continuous imaging of the needle in its course toward the intended target, with less chance of insertion into the nerve. Finally, the use of US imaging allows ongoing evaluation of the disposition of the local anesthetic solution as it is injected, resulting in improved accuracy, higher degree of efficacy, shorter time required for block placement, more rapid onset of anesthesia, and increased duration of block [2]. While some practitioners prefer to use PNS in concert with US guidance, this has not been shown to enhance block success for femoral nerve block [62].

Surgeon-directed, specific local infiltration analgesia (LIA) during the surgery is becoming more popular during total knee arthroplasty. Some investigators have attempted to examine the effects of these techniques in ACLR as well. Dauri et al. performed a randomized trial in ALCR patients, of continuous FNB for postoperative analgesia, versus continuous infusion of ropivacaine into the patellar tendon donor site in concert with intra-articular infusion [12]. All patients received single-shot femoral and sciatic blocks. Pain scores at 12 and 24 h were lower in the group with the femoral nerve catheter infusion, as were oral analgesic requirements. In a comparative trial of LIA vs. femoral block for postoperative analgesia after ACLR, Kristensen reported no differences in pain or opioid consumption between the two groups [39].

9.4.3.3 Continuous PNB Techniques

Peripheral nerve block catheters allow for continuous infusion of local anesthetic solutions to provide ongoing analgesia after painful extremity surgeries. Most practitioners leave them in place for 48–72 h. Continuous techniques may be used for inpatients [30] as well as outpatients [66], in which case patients go home with a disposable pump and remove the catheter themselves. Catheters allow for prolonged pain relief, improved analgesia compared to opioids [58], reduced opioid use and side effects [29, 30], improved sleep and patient satisfaction [30], and earlier discharge from the hospital [6, 8], in studies in which this has been specifically investigated. Further, they allow a degree of titration, with adjustment of concentration or flow rates, that is not possible with single-shot blocks, as well as the ability to turn the infusion off immediately if any symptoms of toxicity should occur or if the extremity becomes insensate [50]. Multiple-day infusions of dilute concentrations of local anesthetic at standard infusion rates appear to be safe in those with normal volume of distribution and hepatic/renal function [35].

In a randomized, blinded, controlled trial to evaluate methods of postoperative analgesia for ACL reconstruction, Williams and colleagues compared the effectiveness of continuous femoral nerve block to either single-shot block or no block at all [75]. In this prospective investigation of 270 patients, pain scores for those with continuous block were significantly lowered on postoperative days 1–3, compared to those with sham block or single-shot block.

Some disadvantages and adverse effects must be weighed against the benefits offered by continuous nerve blocks. These include the potential for catheter colonization and local or systemic infection, as well as technical problems, which were noted in 18 % of cases in a large, multicenter European study of multiple different catheter types [9]. Nerve injury, while unusual with continuous blocks, must nonetheless remain a concern [9].

9.4.3.4 Safety and Complications of Nerve Blocks

Femoral block is considered relatively safe, with low likelihood of nerve injury [5, 65]. However, some authors have found evidence of prolonged quadriceps weakness, both by direct measurement and assessment of function. Krych et al. performed a retrospective study of 196 patients undergoing patellar tendon autograft ACLR [40]. The primary outcome was isokinetic quadriceps strength plus functional testing at 6 months after the surgery. The authors reported significantly reduced quadriceps strength in the group that had received continuous FNB after surgery, compared to the group without nerve block, and both vertical jump and single jump were impacted at this time point, though return to sports was not different between the groups. In a similar, retrospective study in pediatric and adolescent patients, Luot et al. reported measurably lower quadriceps strength at 6 months after surgery, although there was no difference in function [44]. This has led some orthopedists to avoid the use of FNB, while others favor use of the ACB in its place, to avoid impeding quadriceps function, which is subject to many adverse influences in the perioperative period, including preexisting muscle atrophy in the aftermath of the injury, tourniquet use in the operating room, reflex inhibition of muscle contraction due to pain in the postoperative period, and postsurgical inflammatory influences.

Peripheral nerve blockade may contribute to, or cause, postoperative neurologic dysfunction. Reports of serious nerve injury with femoral nerve blockade have ranged from 0.03 % [5] to approximately 0.5 % [9]. Authors of a review reported a mean incidence of 0.34 % [62]; however, permanent injury was very rare. These reports are from the era before US guidance, which may help to reduce the likelihood of severe nerve injury from needle trauma.

Other concerns related to peripheral nerve blockade include bleeding, infection, and systemic toxicity. Infection with single-shot blocks is incredibly rare but may occur with indwelling catheters, as noted above. Damage to blood vessels or hematoma is very unlikely when using ultrasound guidance but may occur with blind/landmark techniques. LAST, usually manifest as central nervous system excitation (confusion, hallucinations, seizure), may occur in as many as 1 in 1,000 cases when ultrasound is not used [56]. However, severe cardiac toxicity with cardiovascular collapse appears to be much less likely to occur [5].

9.4.3.5 Technique for Nerve Stimulator-Guided Femoral Nerve Block with Catheter Insertion

With the patient in supine position, the operator needs to carefully avoid external rotation in the operative leg. The target point for the needle insertion is located at the superior aspect of the thigh, at the femoral crease, approximately 5 cm distal to the inguinal ligament (Fig. 9.4a, b). If the anesthetist is working on the right thigh, he needs to place his right index finger base on the zenith point and directs his hand toward the navel; the tip of the middle finger finds the inguinal crease, where the femoral artery pulse is. This point allows one to identify the femoral nerve, if it is not possible to locate the corresponding artery. After the infiltration of mepivacaine 1–2 % 1–2 ml, a Tuohy needle introducer (18 G, 10 cm) is inserted and connected to a neurostimulator,

Fig. 9.4 (**a**) Use of ultrasound guidance to perform adductor canal block. (**b**) Ultrasound image of needle adjacent to saphenous nerve and femoral artery in the adductor canal, before injection of local anesthetic

set with a current intensity of 1–1.5 mA, at a frequency of 2 Hz. The needle is introduced with the tip toward the nervous pathway, directed to the navel, inclined at a 30–40° angle to the skin of the thigh (Fig. 9.5). The femoral nerve must be approached by the needle above the inguinal crease before it dichotomizes into its terminal branches. This method allows a complete analgesia of the areas innervated by the femoral nerve.

After obtaining the appropriate muscle twitching, confirmed by a symmetrical sliding of the patella, the intensity of stimulating current is progressively reduced, while the position of the needle is adjusted with small movements, in order to preserve an adequate muscle jerk, until the current is less than or equal to 0.4 mA. At this point the local anesthetic is injected and a 20 G catheter is introduced, progressing 3–4 cm beyond the tip of the Tuohy needle.

The block is obtained by injecting levobupivacaine 0.5 % 20 ml (or mepivacaine 1.5–2 % 10 ml plus levobupivacaine 0.5 % 10 ml). To avoid the risk of intravascular injection, it is recommended to administer the volume of local anesthetic in small boluses of 5 ml, with repeated aspiration tests for blood during the procedure. It is possible to guarantee a continuous infusion of levobupivacaine 0.125–0.25 % at 5–7 ml/h, with an elastomeric pump. If the pump allows for patient-controlled regional anesthesia (i.e., self-administration of boluses of local anesthetic), it can be set as follows: infusion rate of 5 ml/h, 2–5 ml as patient-controlled bolus, with a lockout period of 10–20 min, and a maximal infusion amount of 10–12 ml/h.

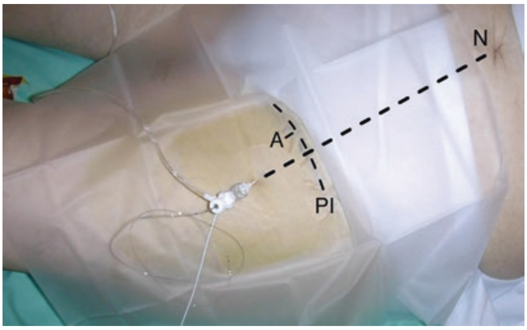

Fig. 9.5 Femoral nerve continuous block with Borghi's personal technique: introduction of the catheter through the Tuohy needle. *N* navel, *A* femoral artery, *PI* inguinal plica

Conclusion

ACLR produces substantial postoperative pain. Most of this appears to be in the femoral nerve distribution, but the sciatic nerve may also be affected, especially when a hamstring autograft is utilized. Neuraxial anesthesia offers several advantages over general anesthesia, including superior early pain control and reduced PONV, but may result in urine retention or delayed discharge from the hospital in ambulatory settings. While multimodal pharmacologic approaches for postoperative analgesia are appropriate for complex joint procedures such as ACLR, the inclusion of peripheral nerve blockade, either in the form of femoral or adductor canal blockade, provides superior pain control to medications alone. Further research is required to clearly elucidate the long-term effect of femoral nerve blockade upon quadriceps function.

References

1. Abdallah FJ, Chan VW, Gandhi R et al (2014) The analgesic effects of proximal, distal or no sciatic nerve block on posterior knee pain after total knee arthroplasty. Anesthesiology 121:1302–1310
2. Abrahams MS, Aziz MF, Fu RF et al (2009) Ultrasound guidance compared with electrical neurostimulation for peripheral nerve block. Br J Anaesth 102:408–418
3. Angst MS (2015) Intraoperative use of remifentanil for TIVA: postoperative pain, acute tolerance, and opioid-induced hyperalgesia. J Cardiothorac Vasc Anesth 29(Suppl 1):S16–S21
4. Apfel CC, Korttila KK, Abdalla M et al (2004) A factorial trial of six interventions for the prevention of postoperative nausea and vomiting. NEJM 350:1441–1451
5. Auroy Y, Benhamou D, Bargues L et al (2002) Major complications of regional anesthesia in France. Anesthesiology 97:1274–1280
6. Barrington M, Kluger R (2013) Ultrasound guidance reduces the risk of local anesthetic systemic toxicity following peripheral nerve blockade. Reg Anesth Pain Med 38:289–299
7. Brull R, McCartney CJ, Chan VW et al (2007) Neurologic complications after regional anesthesia: contemporary estimates of risk. Anesth Analg 104:965–974

8. Bushnell BD, Sakryd G, Noonan TJ (2010) Hamstring donor-site block: evaluation of pain control after anterior cruciate ligament reconstruction. Arthroscopy 26:894–900
9. Capdevilla X, Pirat P, Bringuier S et al (2005) Continuous peripheral nerve blocks in hospital wards after orthopedic surgery. Anesthesiology 103:1035–1043
10. Centers for Disease Control and Prevention (2011) Vital signs: overdoses of prescription opioid pain relievers, United States, 1999–2008. MMWR 60:1487–1489
11. Chelly JE, Greger J, Gebhard R et al (2001) Continuous femoral blocks improve recovery and outcome of patients undergoing total knee arthroplasty. J Arthroplasty 16:436–445, Arthroplasty
12. Dauri M, Fabbi E, Mariani P et al (2009) Continuous femoral nerve block provides superior analgesia compared with continuous intra-articular and wound infusion after anterior cruciate ligament reconstruction. Reg Anesth Pain Med 34:95–99
13. Davarci I, Tuzcu K, Karcioglu M et al (2013) Comparison between ultrasound-guided sciatic-femoral nerve block and unilateral spinal anaesthesia for outpatient knee arthroscopy. J Int Med Res 41:1639–1647
14. De Oliveira Jr GS, Almeida MD, Benzon HT et al (2011) Perioperative single does systemic dexamethasoine for postoperative pain. Anesthesiology 115: 575–580
15. Dilberovic F, Kapur E, Wong C et al (2007) Functional regional anesthesia anatomy. In: Hadzic A (ed) Textbook of regional anesthesia and acute pain management. McGraw-Hill, New York, pp 43–79
16. Espelund M, Fomsgaard JS, Haraszuk J et al (2013) Analgesic efficacy of ultrasound-guided adductor canal block after arthroscopic anterior cruciate ligament reconstruction. Eur J Anaesthesiol 30:422–428
17. Espelund M, Grevstad U, Jaeger P et al (2014) Adductor canal blockade for moderate to severe pain after arthroscopic knee surgery. Acta Anaesthesiol Scand 58:1220–1227
18. Fauno P, Bent C, Svend E et al (2015) Analgesic effect of hamstring block after anterior cruciate ligament reconstruction compared with placebo: a prospective, randomized trial. Arthroscopy 31:63–68
19. Franco CD, Buvanendran A, Petersohn JD et al (2015) Innervation of the anterior capsule of the human knee. Reg Anesth Pain Med 40:363–368
20. Furlan AD, Sandoval JA, Mailis-Gagnon A et al (2006) Opioids for chronic noncancer pain: a meta-analysis of effectiveness and side effects. Can Med Assoc J 174:1589–1595
21. Gerbershagen H, Aduckathil S, Van Wijck A et al (2013) Pain intensity on the first day after surgery: a prospective cohort study comparing 179 surgical procedures. Anesthesiology 118:934–944
22. Graw RP, Ilfeld BM (2012) Toward outpatient arthroplasty: accelerating discharge with ambulatory continuous nerve blocks. Int Anesthesiol Clin 50:111–120
23. Grevstad U, Mathiesen O, Valentiner LS et al (2015) Effect of adductor canal block versus femoral nerve block on quadriceps strength, mobilization and pain after total knee arthroplasty. Reg Anesth Pain Med 40:3–10
24. Hadzic A, Arliss J, Kerimoglu B et al (2004) A comparison of infraclavicular nerve block versus general anesthesia for hand and wrist day-case surgeries. Anesthesiology 101:127–132
25. Hadzic A, Williams B, Karaca PE et al (2005) For outpatient rotator cuff surgery, nerve block anesthesia provides superior same-day recovery over general anesthesia. Anesthesiology 102:1001–1007
26. Hibbard KM, Orebaugh SL, Kentor ML et al (2014) Pain patterns in anterior cruciate ligament reconstruction, and the utility of sciatic nerve blockade for postoperative analgesia. J Anesth Clin Res (online, open access). Accessed 23 Sept 2014
27. Horner G, Dellon AL (1994) Innervation of the human knee joint and implications for surgery. Clin Orthop Relat Res 301:221–226
28. Huddleston JI, Csongradi JJ, Goodman SB, Mihm FG, Halbeis CE (2009) Knee surgery. In: Jaffe RA, Samuels SI (eds) Anesthesiologists manual of surgical procedures, 4th edn. Lippincott Williams and Wilkins, Philadelphia, pp 1013–1029
29. Ilfeld BM, Morey TE, Wang RD et al (2002) Continuous popliteal sciatic nerve block for postoperative pain control at home. Anesthesiology 97:959–965
30. Ilfeld BM, Wright TW, Enneking FK et al (2005) Joint range of motion after total shoulder arthroplasty with and without continuous interscalene nerve block. Reg Anesth Pain Med 30:429–433
31. Iskandar H, Benard A, Ruel-Raymond J et al (2003) Femoral block provides superior analgesia compared with intra-articular ropivacaine after anterior cruciate ligament reconstruction. Reg Anesth Pain Med 28: 29–32
32. Jaeger P, Zaric D, Fomsgaard JS et al (2013) Adductor canal block versus femoral nerve block for analgesia after total knee arthroplasty. Reg Anesth Pain Med 38:526–532
33. Jankowski CJ, Hebl JR, Stuart MJ et al (2003) A comparison of psoas compartment block and spinal and general anesthesia for outpatient knee arthroscopy. Anesth Analg 97:1003–1009
34. Jin F, Chung F (2001) Multimodal analgesia for postoperative pain control. J Clin Anesth 13:524–529
35. Kaloul I, Guay J, Core C (2004) Ropivacaine plasma concentrations are similar during continuous lumbar plexus blockade using the anterior 3-in-1 and the posterior psoas compartment technique. Can J Anaesth 51:52–56
36. Karmakar MK, Ho AM, Li X et al (2008) Ultrasound-guided lumbar plexus block through the acoustic window of the lumbar ultrasound trident. Br J Anaesth 100:533–538
37. Kissin I, Brown PT, Bradley EL (1991) Magnitude of acute tolerance to opioids is not related to their potency. Anesthesiology 75:813–815
38. Korhonen A-M, Valanne JV, Jokela RM et al (2004) A comparison of selective spinal anesthesia with hyperbaric bupivacaine and general anesthesia with

desflurane for outpatient knee arthroscopy. Anesth Analg 99:1668–1673

39. Kristensen PK, Pfeiffer-Jensen M, Storm JO et al (2014) Local infiltration analgesia is comparable to femoral nerve block after anterior cruciate ligament reconstruction with hamstring tendon graft: a randomized controlled trial. Knee Surg Sports Traumatol Arthrosc 22:317–323
40. Krych A, Arutyunyan G, Kuzma S et al (2015) Adverse effect of femoral nerve block on quadriceps strength and function after ACL reconstruction. J Knee Surg 28:83–88
41. Leah PM, Heath EM, Balleine BW et al (2016) Chronic morphine reduces surface expression of δ-opioid receptors in subregions of rostral striatum. Neurochem Res 41:500–509.
42. Liu SS, Strodbeck WM, Richman JM et al (2005) A comparison of regional versus general anesthesia for ambulatory anesthesia: a meta-analysis of randomized controlled trials. Anesth Analg 101:1634–1642
43. Lundblad M, Forssblad M, Eksborg S et al (2011) Ultrasound-guided infrapatellar nerve block for anterior cruciate ligament repair: a prospective, randomized, double-blind, placebo-controlled clinical trial. Eur J Anaesthesiol 28:511–518
44. Luo TD, Ashraf A, Dahm DL et al (2015) Femoral nerve block is associated with persistent strength deficits at 6 months after anterior cruciate ligament reconstruction in pediatric and adolescent patients. Am J Sports Med 43:331–336
45. Macintyre PE, Loadsman JA, Scott DA (2011) Opioids, ventilation and pain management. Anaesth Intensive Care 39:545–549
46. Mall NA, Chalmers PN, Moric M et al (2014) Incidence and trends of anterior cruciate ligament reconstruction in the United States. Am J Sports Med 42:2363–2370
47. Marhofer P, Schrogendorfer K, Wallner T et al (1998) Ultrasonographic guidance reduces the amount of local anesthetic for 3-in-1 blocks. Reg Anesth Pain Med 23:584–588
48. Martin WR, Eades CG (1961) Demonstration of tolerance and physical dependence in the dog following a short-term infusion of morphine. J Pharmacol Exp Ther 133:262–267
49. McCartney CJL, Brull R, Chan VWS et al (2004) Early but no long-term benefit of regional compared with general anesthesia for ambulatory hand surgery. Anesthesiology 101:461–467
50. McGraw RP III, Ilfeld BM (2012) Toward outpatient arthroplasty: accelerating discharge with ambulatory continuous peripheral nerve blocks. Int Anesthesiol Clin 50:111–125
51. Miller MD (2011) Single bundle anterior cruciate ligament repair. In: Miller MD, Wiesel SW (eds) Operative techniques in sports medicine surgery. Wolters-Kluwer, Philadelphia, pp 335–343
52. Moore JG, Ross SM, Williams BA (2013) Regional anesthesia and ambulatory surgery. Curr Opin Anesthesiol 26:652–660
53. Mulroy MF, Larkin KL, Batra MS et al (2001) Femoral nerve block with 0.25% or 0.5% bupivacaine improves postoperative analgesia following outpatient arthroscopic anterior cruciate ligament repair. Reg Anesth Pain Med 26:24–29
54. Nair GS, Abrishami A, Lermitte J et al (2009) Systematic review of spinal anaesthesia using bupivacaine for ambulatory knee arthroscopy. Br J Anaesth 102:307–315
55. O'Donnell D, Manickam B, Perlas A et al (2010) Spinal mepivacaine with fentanyl for outpatient knee arthroscopy surgery. Can J Anaesth 57:32–38
56. Orebaugh SL, Kentor ML, Williams BA (2012) Adverse outcomes associated with nerve stimulator-guided and ultrasound-guided peripheral nerve blocks by supervised trainees. Reg Anesth Pain Med 37:577–582
57. Prof C, Prof S (2011) Treatment of acute postoperative pain. Lancet 377:2215–2220
58. Richman JM, Liu SS, Courpas G et al (2006) Does continuous peripheral nerve block provide superior pain control to opioids? A meta-analysis. Anesth Analg 102:248–257
59. Scuderi PE, James RL, Harris L et al (2000) Multimodal antiemetic management prevents early postoperative vomiting after outpatient laparoscopy. Anesth Analg 91:1408–1417
60. Schloss B, Bhalla T, Klingele K et al (2014) A retrospective review of femoral nerve block for postoperative analgesia after knee surgery in the pediatric population. J Pediatr Orthop 34:459–461
61. Sinatra RS, Torres J, Bustos AM (2002) Pain management after major orthopedic surgery: current strategies and new concepts. J Am Orthop Surg 10: 117–125
62. Sites BD, Beach ML, Chinn CD et al (2009) A comparison of sensory and motor loss after a femoral nerve block conducted with ultrasound versus ultrasound and nerve stimulation. Reg Anesth Pain Med 34:508–513
63. Sites BD, Taenzer AH, Herrick MD et al (2012) Incidence of local anesthetic systemic toxicity and postoperative neurologic symptoms associated with 12,688 ultrasound-guided nerve blocks. Reg Anesth Pain Med 37:478–482
64. Skolnik A, Gan TJ (2014) Update on the management of postoperative nausea and vomiting. Curr Opin Anesthesiol 27:605–609
65. Stein BE, Srikumaran U, Tan EW et al (2012) Lower-extremity peripheral nerve blocks in the perioperative pain management of orthopaedic patients. J Bone Joint Surg 94(e167):1–13
66. Swanson JD, Bay N, Loose E et al (2006) Outpatient management of continuous peripheral nerve catheters placed using ultrasound guidance. Anesth Analg 103:1436–1443
67. Taha AM (2012) Ultrasound-guided obturator nerve block. Anesth Analg 114:236–239
68. Turan A, Belley-Cote EP, Vincent J et al (2015) Methylprednisolone does not reduce persistent pain after cardiac surgery. Anesthesiology 123:1404–1410

69. White PF, Issioui T, Skrivanek GD et al (2003) The use of a continuous popliteal sciatic nerve block after surgery involving the foot and ankle. Anesth Analg 97:1303–1309
70. White PF (2005) The changing role of non-opioid analgesic techniques in the management of postoperative pain. Anesth Analg 101:S5–S11
71. White P, Kehlet H, Neal J et al (2007) The role of the anesthesiologist in fast-track surgery: from multimodal analgesia to perioperative medical care. Anesth Analg 104:1380–1383
72. Williams BA, Kentor ML, Vogt MT et al (2003) Femoral-sciatic nerve blocks for complex outpatient knee surgery are associated with less postoperative pain before same-day discharge. Anesthesiology 98:1206–1213
73. Williams BA, Kentor ML, Vogt MT et al (2004) Economics of nerve block pain management after anterior cruciate ligament reconstruction. Anesthesiology 100:697–706
74. Williams BA, Matusic B, Kentor ML (2005) Regional anesthesia procedures for ambulatory knee surgery. Int Anesthesiol Clin 43:153–160
75. Williams BA, Kentor ML, Vogt MT et al (2006) Reduction of verbal pain scores after anterior cruciate ligament reconstruction with 2-day continuous femoral nerve block. Anesthesiology 104: 315–327
76. Wulf H, Lowe J, Gnutzman K-H et al (2010) Femoral nerve block with ropivacaine or bupivacaine in day case anterior cruciate ligament reconstruction. Acta Anaesthesiol Scand 54:414–420
77. Young A, Buvanendran A (2012) Recent advances in multimodal analgesia. Anesthesiol Clin 30: 91–95

Anticoagulation Following Anterior Cruciate Ligament Reconstruction

10

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10.1 Introduction

The topic of deep vein thrombosis (DVT) prophylaxis in anterior cruciate ligament (ACL) surgery has become an important topic as the frequency of arthroscopic ACL reconstruction continues to increase. Knee arthroscopy is the most commonly performed procedure in the United States and Europe [18, 34, 45], with annual numbers in the millions [24]. Approximately 100,000 primary ACL reconstructions are performed in the United States annually [36]. Arthroscopic ACL reconstructions are typically done in relatively young, healthy patients, as an outpatient procedure, and with early mobilization and weight bearing. Given these factors, it has been viewed as a low-risk procedure for venous thromboembolism (VTE). This viewpoint has been countered by some arguing that ACL reconstruction should be considered a more high-risk procedure than other arthroscopic knee operations, due to the longer operative time and more invasive nature with drilling of bone tunnels. There is evidence that more invasive operations tend to have a higher risk for developing DVT [37]. This conflict is manifested in the varying practice patterns seen in different countries. Surveys and registries show that pharmacological thromboprophylaxis is prescribed for 17–96 % of all patients undergoing knee arthroscopy [2, 24].

Regardless of the perception of risk, VTE is the most common cause of perioperative mortality following knee arthroscopy [39], and there have been several case reports in the literature of fatal pulmonary emboli after arthroscopic knee operations [19, 39, 51]. This, in addition to the increasing numbers of ACL reconstructions, will ensure that even a low complication rate is not negligible in terms of the overall incidence and significance of VTE. The potential consequences of VTE are the reason for considering thromboprophylaxis after any operation. These consequences include pain associated with symptomatic DVTs, increased risk of recurrent DVT, post-thrombotic syndrome, and the development of pulmonary embolism (PE) as well as death.

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This chapter evaluates the topic of anticoagulation after ACL reconstruction. It will discuss the incidence and diagnosis of DVT, risk factors, and available thromboprophylaxis and highlight available scientific evidence as well as national and international guidelines.

10.2 Incidence of DVT

The reported incidence of DVT after knee arthroscopy and ACL reconstruction varies. Mauck et al. noted an overall incidence of symptomatic VTE of 0.4 % over a 3-month postoperative period [48]. Interestingly, they also mentioned that this observed incidence for postoperative knee arthroscopy VTE was 14-fold higher than the general population, matched for age and sex. Maletis et al. also demonstrated a very low incidence of symptomatic VTE following knee arthroscopy with 0.25 % developing DVT and 0.17 % developing PE [45].

The incidence of DVT after knee arthroscopy in prospective studies is generally higher as they also detect asymptomatic DVTs. These studies demonstrate a total DVT incidence of 3.5–17.9 % though the rate of asymptomatic DVTs ranged from 39.4 to 100 % [1, 2, 12–16]. In addition, of the seven studies that discussed DVT location, there was a high incidence of distal calf vein thrombosis of 72.7–100 % [12, 13, 34, 65, 67, 73]. Ettema et al. was an outlier where only 1 of 3 (33.3 %) patients with a DVT had a distal thrombosis [18]. A meta-analysis by Ilahi et al. evaluated six prospective studies with universal screening after knee arthroscopy and found a pooled DVT incidence of 9.9 %, with 83 % of these being distal [35]. Generally, distal DVTs are asymptomatic and have a rate of proximal progression ranging from 1.9 % to 23 % [38, 47]. This rate is highly dependent on the amount of clot burden, baseline versus transient risk factors, and the use of anticoagulation.

Jameson et al. specifically evaluated complications of ACL reconstruction. This retrospective study has the largest population of ACL reconstructions with 13,941 patients and found an incidence of 0.3 % for DVT and 0.18 % for PE [36]. Studies that prospectively looked at ACL reconstruction reported a DVT incidence of 1.5–33 % [1, 11–13, 37, 66, 67, 77]. Again, a typically higher rate of asymptomatic DVT is demonstrated at 44–100 % [1, 11, 15, 37, 66, 67, 77], and there was generally a higher proportion of distal thrombosis ranging from 78 to 100 % [1, 37, 66, 67, 77].

A recently published systematic review focusing on DVT and PE after ACL reconstruction identified six studies with a total of 692 patients. None of the patients in this study received postoperative pharmacological anticoagulation. Fifty-eight patients (8.4 %) developed a DVT (81 % distal), and one patient (0.2 %) had a symptomatic PE. Twenty-seven percent of DVT episodes were reported to be symptomatic [17].

10.3 Diagnostic Tests

Over the years, multiple different ways for diagnosing DVT have been established and used. One of the simplest methods is clinical diagnosis, which includes symptoms of calf or thigh pain, tenderness, and leg swelling, all of which can be easily masked after lower extremity surgery. These symptoms are vague and nonspecific and may not even be present in patients with DVT. Looking at the combined incidence of DVT in 15 studies, only 35 % (94/270) were symptomatic [1, 6, 11–13, 15, 17, 23, 31, 34, 45, 56, 60, 61, 67, 68]. As clinical diagnosis is an unreliable method for the detection of DVT, other diagnostic methods have developed out of necessity.

Ascending contrast venography is considered the gold standard for detection of deep vein thrombosis. However, it requires contrast injection and therefore is invasive in nature. It may cause deep venous thrombosis or ulceration from contrast extravasation and cannot be performed in pregnant patients or those allergic to contrast. Due to these side effects, other forms of detection with lower risks have been developed to replace venography. Plethysmography [44] was used more commonly in the past but has become a historical test with time [64]. Computed tomography (CT) scan [69] and magnetic resonance venography (MRV) [9, 59] are receiving some attention as possible methods, although their clinical use is limited by radiation exposure as well as cost. CT scan is more commonly used in the diagnosis of PE (Fig. 10.1). Ultrasound currently remains the most commonly used method of DVT detection. This is likely because ultrasound is noninvasive and low cost and has minimal risk. However, its accuracy can be adversely affected by morbid obesity, edema, experience of the ultrasonographer, tenderness, and patient inability to tolerate exam and may not be performed if certain bandages or casts are present [78].

There are varying types of ultrasound, which include compression ultrasound (B-mode imaging), Doppler waveform imaging, and color Doppler imaging. B-mode imaging creates images of the vessels that can be analyzed for alteration of blood flow around a filling defect or echogenic material within the lumen, and compression is added to evaluate the amount of compressibility of the vein (decreased if a thrombus is present) (Figs. 10.2, 10.3, 10.4, and 10.5). Both Doppler waveform and color Doppler imaging use sound or color, respectively, to better identify vessels and look for changes or absence of blood flow. Duplex ultrasound is the combination of

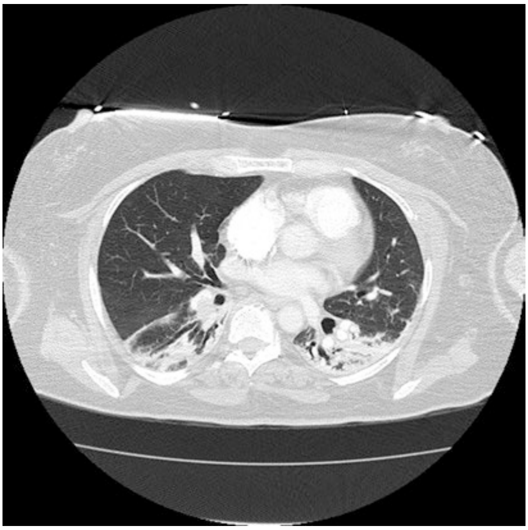


Fig. 10.1 A CT scan of the chest with PE protocol of a healthy 50-year-old patient who underwent elective orthopedic surgery and presented 1-week postoperatively with a massive PE. She had no risk factors other than the use of a topical vaginal estrogen ointment

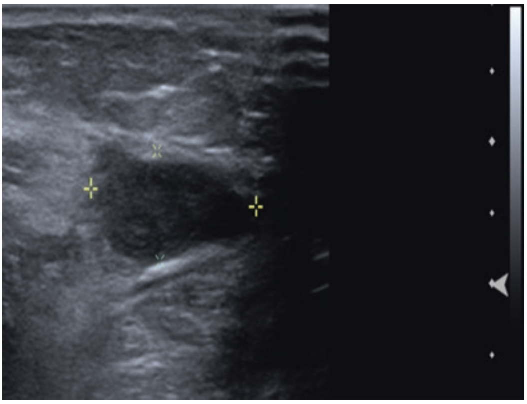


Fig. 10.3 Echogenic material within the vein demonstrating a thrombus

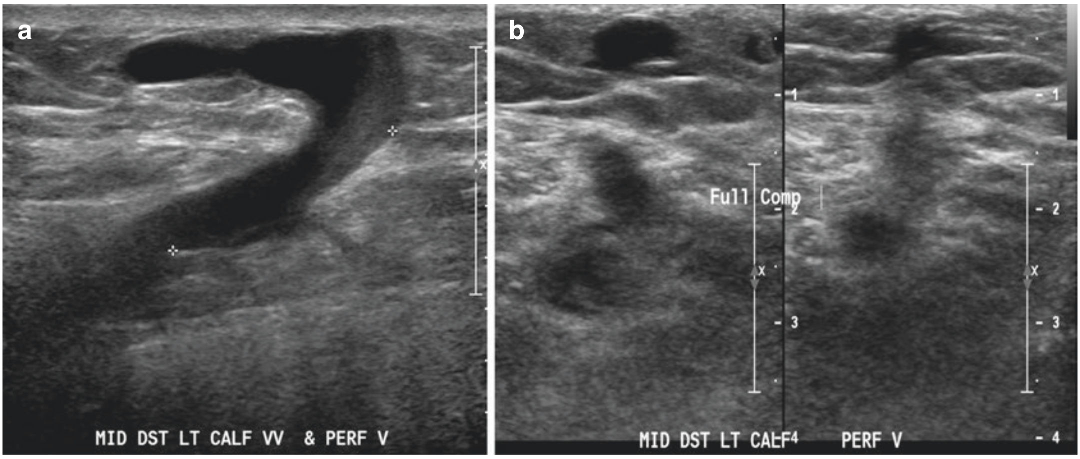


Fig. 10.2 Compression ultrasound (B-mode imaging) showing (**a**) the vein with an open lumen and (**b**) full compression of the vein, indicating absence of thrombus

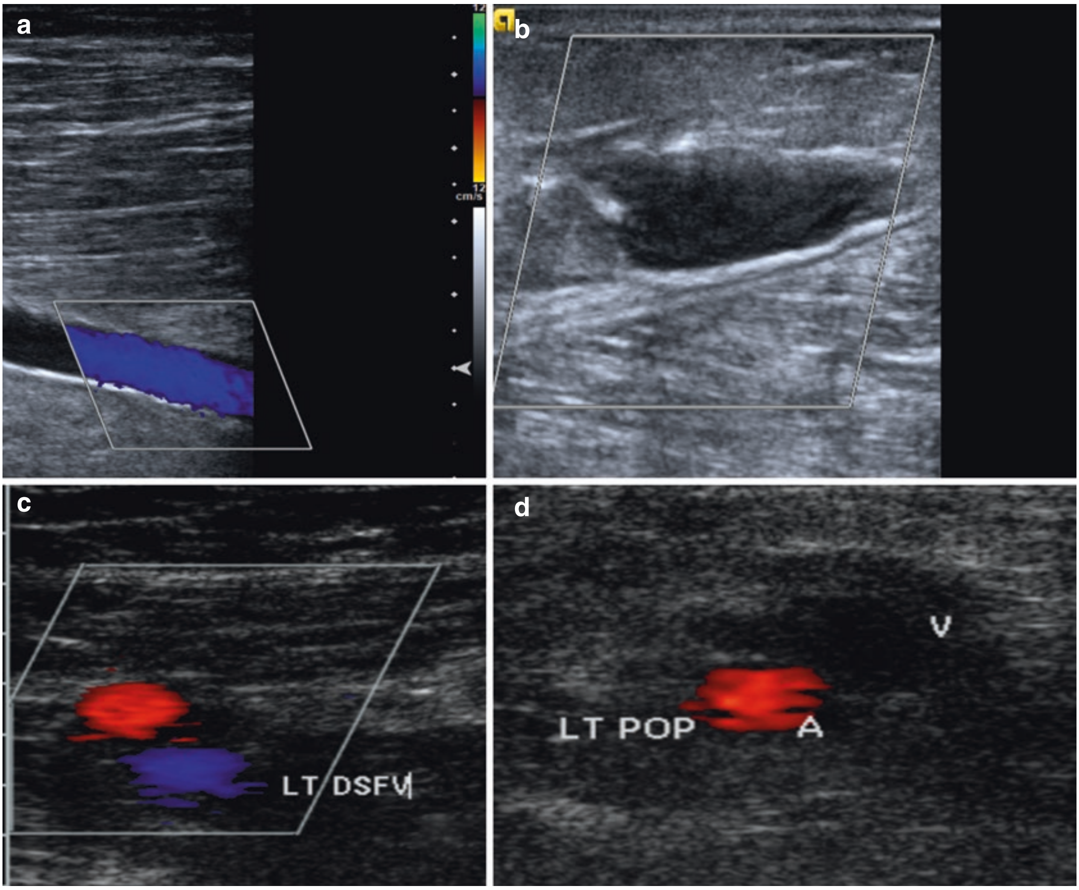


Fig. 10.4 Color Doppler imaging showing (**a**) color flow in the lumen, (**b**) absence of color flow in the lumen suggesting a clot, (**c**) an example of venous and arterial Doppler with a flow in both, and (**d**) image showing a flow in the artery, but not in the vein, indicating a clot

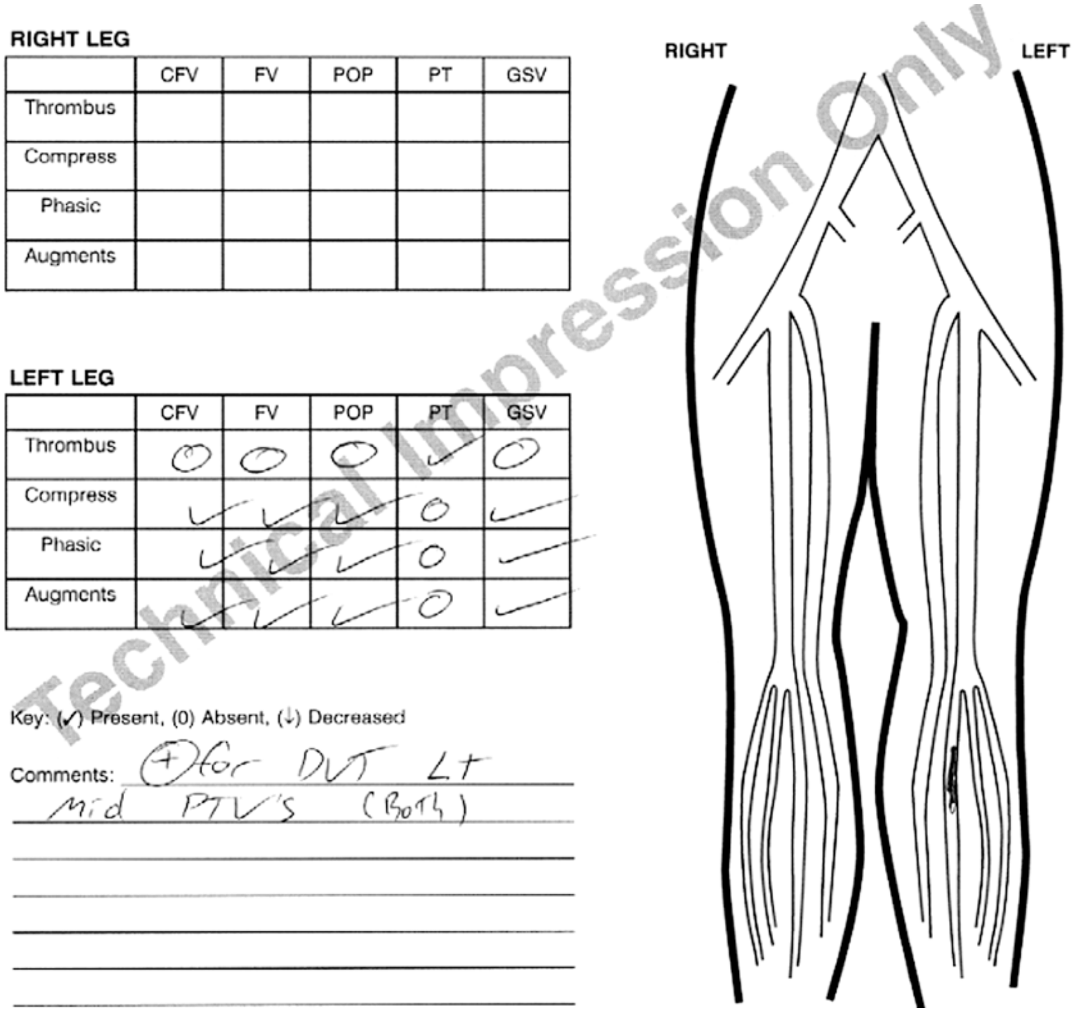
compression ultrasound with either color or Doppler waveform imaging. The sensitivity and specificity of ultrasound depend on the form of ultrasound used, the location of the thrombus, and whether the patient is symptomatic or not [78]. A meta-analysis of studies using various ultrasound methods to detect DVT in asymptomatic patients found a pooled sensitivity of 62 % and specificity of 97 % [71]. Proximal DVT was significantly better with a sensitivity of 95 % and specificity of 100 % [71]. A meta-analysis that looked at studies with only symptomatic patients found a pooled sensitivity of 89.7 % for detecting any DVT, 94.2 % for proximal DVT, and 63.5 % for distal DVT [23]. In a high-risk postoperative patient with concern for DVT but a negative ultrasound, venography or serial ultrasounds may need to be considered. The diagnostic criteria for a DVT on ultrasound are displayed in Table 10.1.

10.4 Risk Factors

Multiple risk factors, both patient and procedure specific, may affect a patient's overall risk for developing VTE.

10.4.1 Patient-Specific Factors

Patient-specific risk factors include age, gender, previous history of VTE, oral contraceptives or hormone replacement therapy, varicose veins, smoking, obesity, history of malignancy,



RIGHT LEG

	CFV	FV	POP	PT	GSV
Thrombus					
Compress					
Phasic					
Augments					

LEFT LEG

	CFV	FV	POP	PT	GSV
Thrombus	0	0	0	✓	0
Compress	✓	✓	✓	0	✓
Phasic	✓	✓	✓	0	✓
Augments	✓	✓	✓	0	✓

Key: (✓) Present, (0) Absent, (↓) Decreased

Comments: ⊕ for DVT Lt
Mid PTV's (Both)

Fig. 10.5 Diagram for reporting DVT found on ultrasound examination

Table 10.1 Ultrasound diagnostic criteria for DVT

B-mode/compression imaging	Color/waveform Doppler imaging
Intraluminal echogenic material	Absent intraluminal signal (no flow)
Blood flow around intraluminal filling defect	Color flow around an intraluminal filling defect
Partially compressible or non-compressible vein	Diminished or absent flow response with augmentation maneuvers (squeezing distal portion of the vein)
Increase in vein diameter	Non-phasic, continuous flow (with respirations)
	No change or reflux with Valsalva maneuver

pregnancy, and an inherited or acquired thrombophilia.

Increasing age is considered an independent risk factor for VTE [8, 24, 31], and multiple studies show a positive correlation between increasing age and incidence of DVT [36, 45, 46, 63, 65, 67, 77]. One study indicated that hazard ratio for VTE after knee arthroscopy increased by 34 % for every 10-year increase in age [48].

A number of studies have analyzed gender as a risk factor for VTE after knee arthroscopy or ACL reconstruction. The overwhelming consensus appears to be that there is no difference in incidence between males and females [13, 36, 45, 46, 67]. Only one study found a higher risk of DVT in female patients, but their female population had a higher age than their male counterparts [77].

Another factor that can affect the gender divide is the use of oral contraceptives (OCP) or hormone replacement therapy (Fig. 10.1). While the use of these in general is considered to be an independent risk factor for VTE, the literature with respect to knee arthroscopy and ACL reconstruction is more conflicting [24, 31]. Two studies found no association between the use of OCPs and incidence of DVT postoperatively [12, 65], while a third retrospective study found that there was a higher incidence of DVT in patients who had received or refilled a prescription for OCP in 4 months leading up to knee arthroscopy surgery [45]. They found the odds of developing a DVT, adjusted for age, were 2.54 times higher if the patient was taking OCPs [45].

Most studies did not find obesity (typically defined as BMI >30) alone related to increased incidence of DVT [48, 61, 65, 67]. One study did find that in the presence of at least two other patient-specific risk factors, a BMI >30 contributed to an increased incidence of DVT [12].

The presence of varicosity or chronic venous insufficiency was not found to be associated with DVT incidence in two studies [12, 65], but was the only statistically significant risk factor in another study [61].

A personal history of previous VTE has long been associated with an increased risk of a recurrent VTE. One study confirmed it as an independent risk factor with a relative risk of 8.2 for the development of DVT [12]. However, two other studies did not find an association between increased incidence of DVT post-arthroscopy and a previous history of VTE [13, 65].

Smoking is not frequently assessed in the literature, though is considered a classic risk factor for DVT [24]. One study found no correlation with incidence of DVT [46], while another found that it contributed to an increased incidence of DVT when in combination with one or more other patient-specific risk factors [12].

Another risk factor associated with developing DVT is air travel, though it has not been specifically evaluated after knee arthroscopy or ACL reconstruction. Recent studies have shown a two- to fourfold increased risk [42]. Several underlying causes have been identified including immobilization and hypoxia [6]. Air travel appears to be an especially strong risk factor for those with a genetic or acquired hypercoagulability [7]. However, even in the healthy population, some people were found to have coagulation activation after air travel [62]. A study by Schreijer et al. showed that 17 % of healthy subjects had increased thrombin-antithrombin complexes after an 8-h flight, but not after an 8-h movie marathon [62]. The remaining subjects in this study showed no activation of coagulation.

10.4.2 Procedure-Specific Factors

Orthopedic surgery in and of itself is an independent risk factor for DVT as it causes damage to muscle and bone, which triggers the release of coagulation factors and activation of platelets at the surgical site, which in turn activate local clotting processes [8, 40]. In addition, surgical stress and pain can provoke catecholamine release intravascularly, which also increase blood coagulability [8, 40].

The use of a tourniquet has been shown to increase blood coagulability during surgery, which may be related to tissue ischemia or pain [15, 40]. Hirota et al. evaluated tourniquet use and the amount of pulmonary emboli detected in the right atrium after tourniquet release in a couple different studies [32, 33]. They discovered that an increase in pulmonary emboli after tourniquet release is dependent on the duration of tourniquet inflation. In clinical studies, simply the use of a tourniquet during knee arthroscopy or ACL reconstruction is not associated with an increased incidence of DVT [46, 61, 63]. However, tourniquet time has conflicting evidence. Several studies did not find any correlation between tourniquet time and incidence of DVT postoperatively [12, 67, 77]. However, other studies demonstrated an increased incidence of DVT with longer tourniquet times >60 or 120 min [13, 15, 37, 46].

Most literature did not find an association between surgical duration and incidence of DVT [13, 46, 61, 67, 77]. It has been suggested that the type of anesthesia, either general or epidural/spinal, may have an effect on the incidence of DVT. However, two studies that evaluated regional/epidural anesthesia versus general anesthesia found no difference in risk of DVT [13, 61].

10.5 Mechanical and Pharmacological Thromboprophylaxis

The decision-making process involved in choosing the right form of thromboprophylaxis for a specific patient starts with proper risk assessment [8]. The American College of Chest Physicians (ACCP) divides patients into low, moderate, high, and very high risk based on the expected incidence of deep venous thrombosis (DVT) and pulmonary embolism (PE) in the absence of prophylaxis (Table 10.2) [58]. Based on this risk stratification, they recommend different types of prophylaxis. This can include mechanical prophylaxis such as sequential compression devices and compression stockings, or pharmacological prophylaxis. Some of the more commonly used ones are discussed below.

10.5.1 Sequential Compression Devices (SCD)

Pneumatic/sequential compression devices are frequently used during and immediately after orthopedic surgery. SCDs utilize sleeves with separated areas or pockets of inflation, which works to squeeze on the limb in a “milking action” (Fig. 10.6). The most distal areas will initially inflate, and subsequent pockets will

Fig. 10.6 A patient undergoing left knee arthroscopy. The right leg is placed in a sequential compression device to prevent DVT

Table 10.2 ACCP VTE risk classification system

	Low risk	Moderate risk	High risk	Very high risk
	Uncomplicated minor surgery in patients <40 years without risk factors	Uncomplicated surgery in patients 40–60 years without risk factors Major surgery in patients <40 years without risk factors Minor surgery in patients with risk factors	Major surgery in patients >60 years with additional risk factors	Major surgery in patients >40 years with prior VTE, malignancy, hypercoagulable state, elective major orthopedic surgery or hip fracture, polytrauma, spinal cord injury
Distal leg DVT	2	10–20	20–40	40–80
Proximal leg DVT	0.4	2–4	4–8	10–20
Clinical PE	0.2	1–2	2–4	4–10
Fatal PE	0.002	0.1–0.4	0.4–1	1–5
Successful preventing strategies	No specific measures	Low-dose unfractionated heparin Q12h, low-molecular-weight heparin, fondaparinux, SCD, compression stockings	Low-dose unfractionated heparin Q8h, low-molecular-weight heparin, fondaparinux, SCD	Low-molecular-weight heparin, oral anticoagulants, SCD

follow in the same manner. The pneumatic compression is thought to prevent venous stasis and encourage blood flow in the extremity while the patient is not actively moving the operative as well as the non-operative limb [50]. However, its use is mostly limited to the hospital setting.

10.5.2 Compression Stockings

Elastic compression stockings can be used in the immediate postsurgical period while the patient is recovering at home (Fig. 10.7). They reduce the diameter of distended veins and cause an increase in venous blood flow velocity and valve effectiveness. Compression stockings have been shown to help decrease venous pressure and prevent venous stasis [53]. Knee or thigh high compression stockings can therefore help prevent the formation of blood clots in the lower legs. Thromboembolism-deterrent (TED) hose are a type of gradient compression stocking. Gradient compression stockings provide the highest level of compression at the ankle which gradually lessens toward the top of the stocking. They have been shown to be effective in supporting the venous and lymphatic drainage of the leg, especially when combined with activations of the calf muscles [3]. Mechanical prophylaxis has a strong support for its use from the ACCP [21, 22].

Fig. 10.7 A postsurgical patient wearing bilateral knee high compression stockings to prevent DVT

10.5.3 Aspirin

Aspirin is a salicylate drug which has antiplatelet effect by inhibiting the production of thromboxane. Aspirin is therefore often used to help prevent heart attacks, strokes, and blood clot formation in people at high risk [43]. Its side effects include gastrointestinal bleeding, tinnitus, Reye's syndrome, hives, swelling, and hyperkalemia. It is contraindicated in patients with peptic ulcers, diabetes, gastritis, or a history of gastrointestinal bleeding. Although commonly used as a form of thromboprophylaxis by orthopedic surgeons, the ACCP recommends against the use of aspirin alone for DVT prophylaxis in its most recent guideline due to lack of high-level evidence to support this [27].

10.5.4 Low-Dose Unfractionated Heparin

Heparin is one of the most commonly used pharmacologic DVT prophylaxes, both in orthopedic surgery and in medicine as a whole. It is recommended by the ACCP for patients with moderate, high, and very high risk [27]. Heparin works by binding to the enzyme inhibitor antithrombin III. It then inactivates thrombin and other proteases involved in blood clotting such as factor Xa [10]. Unfractionated heparin is heparin that has not been fractionated to sequester the fraction of molecules with low molecular weight. It is available for intravenous (IV) as well and subcutaneous (SQ) administration. The most common side effects include bleeding, allergic reaction, injection site reaction, increase in liver enzymes, and heparin-induced thrombocytopenia (HIT) [57]. The incidence is up to 5 % of patients treated with unfractionated heparin [57].

10.5.5 Low-Molecular-Weight Heparin

Low-molecular-weight heparin (LMWH) has undergone fractionation with the goal of making its pharmacodynamics more predictable. An example of a commonly used one is enoxaparin

Fig. 10.8 A postsurgical patient receiving a subcutaneous administration of Lovenox in the abdominal region for DVT prophylaxis

(trade name Lovenox, Sanofi, Bridgewater, NJ, USA) (Fig. 10.8). LMWH only consists of the short chains of polysaccharide. It can be dosed less frequently than unfractionated heparin, once or twice a day versus two to three times daily. Other potential benefits of LMWH are a smaller risk of bleeding, osteoporosis, and HIT (1 % versus 5 %). However, an advantage of unfractionated heparin is that it is reversible with protamine sulfate, while the effect of this on LMWH is limited. The use of LMWH does need to be monitored in elderly patients and those with decreased renal function as it is renally cleared.

10.5.6 Fondaparinux

Fondaparinux is an anticoagulant medication chemically related to LMWH. The most common brand name is Arixtra (GlaxoSmithKline, Coraopolis, PA, USA). It is a synthetic pentasaccharide factor Xa inhibitor. In contrast to heparin, fondaparinux does not inhibit thrombin. The risk of HIT is substantially lower than with the use of both unfractionated and LMWH. However, its renal excretion precludes its use in patients with decreased renal function.

10.5.7 Oral Anticoagulants

There are several forms of oral anticoagulation. The most commonly used ones in orthopedic surgery belong to the coumarin family. Coumarins are plant-derived vitamin K antagonists. Warfarin is the most common generic with Coumadin (Bristol-Myers Squibb, New York, NY, USA) as the corresponding brand name. It takes at least 48–72 h for the anticoagulant effect to develop. The effectiveness is monitored by determination of the international normalized ratio (INR) in the patient's blood. For DVT prophylaxis the recommended INR is 2.5. It can be reversed using either vitamin K and/ or the administration of fresh frozen plasma.

Another category is the direct factor Xa inhibitors. The most commonly used example is rivaroxaban (brand name: Xarelto, Janssen Pharmaceuticals, Titusville, NJ, USA). The benefit of this class of medications is that they do not require regular blood monitoring of the INR. However, they are less frequently used because they have only recently become clinically available and have less awareness than some of the other medications listed. Further it is not possible to reverse their effect. Recently there have been several class action law suits regarding specific oral Xa inhibitors secondary to increased bleeding risk. However, medical literature about this is conflicting. A recent small retrospective pilot study showed that after joint replacement surgery, postoperative bleeding occurred in 6.8 % of the patients using rivaroxaban versus in 3.2 % of the patients on enoxaparin ($p<0.0001$) [76]. In contrary, a Cochrane review on the effectiveness of oral direct thrombin inhibitors and oral factor Xa inhibitors showed a similar rate of DVT and PE as compared to other forms of pharmacological anticoagulation and a decreased incidence of bleeding [56].

The last category is direct thrombin inhibitors [14]. Again, these are not very commonly used in orthopedic surgery for the same reason as the factor Xa inhibitors: they do not have a method of monitoring and cannot be quickly reversed. Some examples include argatroban (no brand name, GlaxoSmithKline, Coraopolis, PA, USA) and dabigatran (Pradaxa, Boehringer Ingelheim Pharmaceuticals, Ridgefield, CT, USA).

Most of the oral thromboprophylaxes have been approved for use in hip and knee replacement surgery; however, their use in prophylaxis following ACL reconstruction or knee arthroscopy has not been studied.

One of the biggest considerations with oral anticoagulation is their interaction with certain foods and nutritional supplements. The blood thinning effect can be increased with the use of beer, celery, cranberries, fish oil, garlic, ginger, ginkgo, ginseng, green tea, licorice, niacin, onion, papaya, pomegranate, red clover, soybean, St. John's wort, turmeric, wheatgrass, willow bark, danshen, and feverfew [75]. Foods and supplements that encourage clotting are alfalfa, avocado, cat's claw, coenzyme Q10, and dark leafy greens such as spinach [75]. Grapefruit interferes with some anticoagulant drugs, increasing the amount of time it takes for them to be metabolized out of the body [75].

10.5.8 Inferior Vena Cava (IVC) Filter

An IVC filter is a device which can be inserted into the inferior vena cava by either interventional radiology or vascular surgery. It is designed to prevent emboli from the lower extremities to pass through the vena cava into the lung, causing a PE. There are not many high-level studies on these devices. Therefore, its use is limited to patients with significant contraindications for anticoagulation such as active bleeding and low platelet count, if the ACL surgery was so recent the surgeon is afraid of hemathrosis, if there is a plan to return to the OR in the near future, or in patients with a history of intracranial bleeding or HIT.

The one level I evidence study on the use of IVC filters demonstrated a decreased incidence in PE but an increased incidence of DVT [25, 26]. In addition, this study and other studies have shown many long-term complications of IVC filters, which has led to the introduction of retrievable IVC filters. The ACCP supports the use of IVC filters for those with contraindications to anticoagulation who either have acute PE or acute proximal DVT [20].

10.5.9 Other Considerations

No specific guidelines or consensus exists for the length of prophylactic treatment after knee arthroscopy. The AAOS recommends 10 days of treatment after a knee or hip replacement [30]. Studies that evaluate length of prophylaxis are conflicting. Camporese found no additional benefit with a 14-day LMWH regimen over a 7-day regimen [6], but Marlovits found a significantly reduced incidence of DVT with extended duration enoxaparin post discharge compared to only in-hospital use [46]. Another study noted that 80 % of DVT occurred within the first 14 days post-op [49]. Conversely, an argument can be made to continue DVT prophylaxis until the patient has reached a certain level of mobility, for example, until the patient is able to weight bear, or until they are no longer using crutches.

Another consideration for choosing different kinds of thromboprophylaxis is the associated cost. Generally speaking oral medication is less expensive than injectable medication [70]. However, it is also important whether a patient receives the medication while in the hospital or while at home or at a rehab facility. Often times, insurance companies will cover the use of some medications only in a hospital or rehabilitation setting. For outpatient use in patients with poor or no insurance coverage, oral anticoagulation such as warfarin holds the lowest out of pocket cost.

10.6 Treatment of DVT After ACL Surgery

If a patient is diagnosed with a DVT or PE after ACL surgery, treatment should be initiated immediately. There is some controversy in literature on whether only proximal DVT should be treated, or if distal DVTs warrant treatment as well. Anticoagulation is the mainstay of treatment for DVT. The goal is to prevent further thrombosis, PE (Fig. 10.1), post-thrombotic syndrome, pulmonary hypertension, and death. Post-thrombotic syndrome is a spectrum of morbidities which include leg swelling, fatigue, and venous stasis ulcers [72]. Haas et al. reported an incidence of post-thrombotic syndrome of 24 % 2–4 years after asymptomatic DVT after orthopedic surgery [28].

[redacted]

Fig. 10.9 A patient with multiple medical comorbidities receiving an IV heparin infusion for a DVT as an inpatient

For most patients, LMWH or fondaparinux are the preferred anticoagulants for their ease of use and support in literature [41]. However, unfractionated heparin is used in patients where there is a concern for renal dysfunction or with an increased risk of bleeding which may need to be reversed (Fig. 10.9). Warfarin can be used as well but has to be used with LMWH, fondaparinux, or heparin for the first 5 days until the target INR is reached at 2.5.

DVT can be treated as an outpatient [41], but some patients will need to be admitted to the hospital. Generally, outpatient therapy is supported if patients are reasonable and understand the potential risks and side effects of anticoagulation, are hemodynamically stable, and have low bleeding risk and no renal insufficiency [41]. Admission is recommended for patients with a massive DVT, PE, high bleeding risk, medical comorbidities, or an unfit or unsafe home situation [16]. These patients need to be monitored for adverse effect of the anticoagulation therapy.

Treatment of a thrombus is typically 3 months for a first time, uncomplicated DVT. In patients with significant risk factors or those diagnosed with a PE, treatment can be extended to 6 months or 1 year. Life-long preventive treatment is recommended for those with significant risk factors, such as the presence of a hereditary coagulopathy or those with multiple prior DVTs or PEs.

10.7 Evidence-Based Medicine: Randomized Controlled Trials/Meta-analyses

There is a reasonable body of level I and II literature on DVT prophylaxis after arthroscopic knee surgery. A recent systematic review of literature by Graham et al. identified 26 studies reporting on the incidence of VTE, DVT, and PE after arthroscopic knee surgery [24]. The findings of their review are interesting as they again illustrate the difference in results between the retrospective and prospective studies. When evaluating the occurrence of DVT and PE after arthroscopic knee surgery retrospectively, the incidence was less than 1 %. However, in the prospective studies, where all included patients were screened and thus both asymptomatic and symptomatic DVT and PE were assessed, the incidence was reported to vary from 1 % to as high as 41 % [24]. Various organizations therefore advocate against the routine screening of postsurgical patients with lower extremity venous duplex [27, 29].

The review by Graham et al. also looked at studies evaluating the effectiveness of various pharmacological thromboprophylaxis after knee arthroscopy [24]. They identified six randomized controlled trials [4, 5, 46, 49, 52, 74]. Two of those studies focused specifically on thromboprophylaxis after ACL reconstruction [5, 46]. All six studies evaluated the use of LMWH. Three studies demonstrated a reduced risk of DVT with the use of LMWH [4, 49, 74]. However, the majority of prevented DVTs were distal ones, the clinical significance of which remains unclear [55, 60]. Four studies reported on the bleeding risk with LMWH treatment. Minor bleeding was reported in 2.5–12 % of patients and major bleeding in 0–0.9 % [24].

A meta-analysis by Sun et al. on the efficacy of thromboprophylaxis after arthroscopic knee surgery included 13 prospective studies, 4 of which were randomized trials. They found that the incidence of DVT was 0.1–11.9 % in studies where patients received LMWH versus 1.8–41.2 % in studies where patients received no prophylaxis [68]. Furthermore, they concluded that the rate of proximal DVT in total DVT occurrence could be reduced from 21.3 % to 11.1 % with the use of LMWH [68].

A Cochrane review evaluating various interventions for preventing venous thromboembolism in adults undergoing knee arthroscopy included 4 trials with a total of 527 subjects [54]. They found that the relative risk of any thrombotic event was 0.16 when comparing any type of LMWH to placebo. However, they did state that all but one of these events involved distal venous thrombosis. Adverse events had a relative risk of 2.04 in the LMWH as compared to the placebo subjects. The authors state that there is no strong evidence to conclude that thromboprophylaxis is effective and safe to prevent thromboembolic events in patients with unknown risk factors undergoing arthroscopic knee surgery [54].

10.8 National and International Guidelines

Various guidelines for selecting the appropriate thromboprophylaxis for each patient exist. General guidelines, not specific to orthopedic surgery, are provided by the ACCP [21, 22, 27]. These recommendations are summarized in Table 10.2. They recommend that all hospitals have a formal strategy to address the prevention of DVT and PE. They recommend against the use of aspirin alone as thromboprophylaxis for patients in any of the risk groups. They recommend for mechanical methods of prophylaxis for patients at high bleeding risk. Specifically for arthroscopic surgery, they recommend against routine pharmacological thromboprophylaxis as they consider this a minor surgery in mobile patients [27]. However, they do support the use of LMWH in patients with risk factors for or a history of DVT or PE [27].

Caprini et al. proposed another risk stratification system with the efforts of the THRiFT group [8]. Their guideline follows a scoring form filled out by the treating physician, which includes risk factors associated with the clinical setting and patient-related factors, and recommends a specific thromboprophylaxis based on these combined risk factors [8].

Some orthopedic organizations give recommendations with regard to DVT prophylaxis. The AAOS does provide specific recommendations for patients undergoing knee or hip replacement surgery [30]. However, they have no recommendations for patients undergoing arthroscopic knee surgery or ACL reconstruction [29].

10.9 Conclusions

Although the overall incidence of DVT and PE after arthroscopic ACL reconstruction is low, with the increasing frequency of the procedure, its prevalence is not negligible [17]. Performing a proper risk assessment for each patient should be part of the preoperative evaluation. There are no strict guidelines for the use and choice of DVT prophylaxis, but there is literature available to assist the treating surgeon in making a decision based on the individual patient's risk profile. Early mobilization and mechanical prophylaxis are safe and their use is supported in literature. There are many types of pharmacological prophylaxis, all of which have been shown to reduce the rate of DVT and PE, but all with bleeding risks and other potential serious side effects. Those should therefore be prescribed based on the surgeon's risk assessment of their patient and after a discussion with the patient regarding the potential benefits and risks.

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References

1. Adala R, Anand A, Kodikal G (2011) Deep vein thrombosis and thromboprophylaxis in arthroscopic anterior cruciate ligament reconstruction. Indian J Orthop 45:450–453
2. Ageno W, Dentali F, Imberti D (2004) A survey of thrombosis prophylaxis use in patients undergoing arthroscopy surgery. J Thromb Haemost: JTH 2:1901–1902
3. Blattler W, Zimmet SE (2008) Compression therapy in venous disease. Phlebology/Venous Forum R Soc Med 23:203–205
4. Camporese G, Bernardi E, Prandoni PEA (2008) Low-molecular-weight heparin versus compression stockings for thromboprophylaxis after knee arthroscopy: a randomized trial. Ann Intern Med 149:73–82
5. Canata GL, Chiey A (2003) Prevention of venous thromboembolism after ACL reconstruction: a prospective, randomized study. Int Soc Arthrosc Knee Surg Orthop Sports Med. 2003
6. Cannegieter SC (2012) Travel-related thrombosis. Best practice & research. Clin Haematol 25:345–350
7. Cannegieter SC, Doggen CJ, Van Houwelingen HC et al (2006) Travel-related venous thrombosis: results from a large population-based case control study (MEGA study). PLoS Med 3:e307
8. Caprini JA, Arcelus JI, Reyna JJ (2001) Effective risk stratification of surgical and nonsurgical patients for venous thromboembolic disease. Semin Hematol 38:12–19
9. Carpenter JP, Holland GA, Baum RA et al (1993) Magnetic resonance venography for the detection of deep venous thrombosis: comparison with contrast venography and duplex Doppler ultrasonography. J Vasc Surg 18:734–741
10. Chuang YJ, Swanson R, Raja SM et al (2001) Heparin enhances the specificity of antithrombin for thrombin and factor Xa independent of the reactive center loop sequence. Evidence for an exosite determinant of factor Xa specificity in heparin-activated antithrombin. J Biol Chem 276:14961–14971
11. Cullison TR, Muldoon MP, Gorman JD et al (1996) The incidence of deep venous thrombosis in anterior cruciate ligament reconstruction. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 12:657–659
12. Delis KT, Hunt N, Strachan RK et al (2001) Incidence, natural history and risk factors of deep vein thrombosis in elective knee arthroscopy. Thromb Haemost 86:817–821
13. Demers C, Marcoux S, Ginsberg JS et al (1998) Incidence of venographically proved deep vein thrombosis after knee arthroscopy. Arch Intern Med 158:47–50
14. Di Nisio M, Middeldorp S, Buller HR (2005) Direct thrombin inhibitors. N Engl J Med 353:1028–1040
15. Dong JT, Wang X, Men XQ et al (2015) Incidence of deep venous thrombosis in Chinese patients undergoing arthroscopic knee surgery for cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 23(12):3540–4
16. Douketis JD (2005) Treatment of deep vein thrombosis: what factors determine appropriate treatment? Can Fam Physician 51:217
17. Erickson BJ, Saltzman BM, Campbell KA et al (2015) Rates of deep venous thrombosis and pulmonary embolus after anterior cruciate ligament reconstruction: a systematic review. Sports Health 7(3):261–266
18. Ettema HB, Hoppener MR, Veeger NJ et al (2006) Low incidence of venographically detected deep vein thrombosis after knee arthroscopy without thromboprophylaxis: a prospective cohort study. J Thromb Haemost JTH 4:1411–1413
19. Eynon AM, James S, Leach P (2004) Thromboembolic events after arthroscopic knee surgery. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 20(Suppl 2):23–24
20. Falck-Ytter Y, Francis CW, Johanson NA et al (2012) Prevention of VTE in orthopedic surgery patients: Antithrombotic Therapy and Prevention of Thrombosis, 9th ed: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines. Chest 141:e278S–e325S
21. Geerts W (2009) Prevention of venous thromboembolism: a key patient safety priority. J Thromb Haemost: JTH 7(Suppl 1):1–8
22. Geerts WH, Bergqvist D, Pineo GF et al (2008) Prevention of venous thromboembolism: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines (8th Edition). Chest 133:381S–453S
23. Goodacre S, Sampson F, Thomas S et al (2005) Systematic review and meta-analysis of the diagnostic accuracy of ultrasonography for deep vein thrombosis. BMC Med Imaging 5:6
24. Graham WC, Flanigan DC (2014) Venous thromboembolism following arthroscopic knee surgery: a current concepts review of incidence, prophylaxis, and preoperative risk assessment. Sports Med 44:331–343
25. Greenfield LJ, The PREPIC Study Group (2006) Eight-year follow-up of patients with permanent vena cava filters in the prevention of pulmonary embo-

lism: the PREPIC (Prevention du Risque d'Embolie Pulmonaire par Interruption Cave) Randomized Study. Perspect Vasc Surg Endovasc Ther 18:187–188

26. Group PS (2005) Eight-year follow-up of patients with permanent vena cava filters in the prevention of pulmonary embolism: the PREPIC (Prevention du Risque d'Embolie Pulmonaire par Interruption Cave) randomized study. Circulation 112:416–422
27. Guyatt GH, Eikelboom JW, Gould MK (2012) Approach to outcome measurement in the prevention of thrombosis in surgical and medical patients: antithrombotic therapy and prevention of thrombosis. Chest 141:185S–194S
28. Haas S (2000) Deep vein thrombosis: beyond the operating table. Orthopedics 23:s629–s632
29. Harner CD, Baek GH, Vogrin TM et al (1999) Quantitative analysis of human cruciate ligament insertions. Arthroscopy 15:741–749
30. Hefzy MS, Grood ES, Noyes FR (1989) Factors affecting the region of most isometric femoral attachments. Part II: the anterior cruciate ligament. Am J Sports Med 17:208–216
31. Heit JA (2005) Venous thromboembolism: disease burden, outcomes and risk factors. J Thromb Haemost JTH 3:1611–1617
32. Hirota K, Hashimoto H, Kabara S et al (2001) The relationship between pneumatic tourniquet time and the amount of pulmonary emboli in patients undergoing knee arthroscopic surgeries. Anesth Analg 93:776–780
33. Hirota K, Hashimoto H, Tsubo T et al (2002) Quantification and comparison of pulmonary emboli formation after pneumatic tourniquet release in patients undergoing reconstruction of anterior cruciate ligament and total knee arthroplasty. Anesth Analg 94:1633–1638, table of contents
34. Hoppener MR, Ettema HB, Henny CP et al (2006) Low incidence of deep vein thrombosis after knee arthroscopy without thromboprophylaxis: a prospective cohort study of 335 patients. Acta Orthop 77:767–771
35. Ilahi OA, Reddy J, Ahmad I (2005) Deep venous thrombosis after knee arthroscopy: a meta-analysis. Arthrosc: J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 21:727–730
36. Jameson SS, Dowen D, James P et al (2012) Complications following ACL reconstruction in the English NHS. Knee 19:14–19
37. Jaureguito JW, Greenwald AE, Wilcox JF et al (1999) The incidence of deep venous thrombosis after arthroscopic knee surgery. Am J Sports Med 27:707–710
38. Kakkar VV, Howe CT, Flanc C et al (1969) Natural history of postoperative deep-vein thrombosis. Lancet 2:230–232
39. Kieser C (1992) A review of the complications of arthroscopic knee surgery. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 8:79–83
40. Kohro S, Yamakage M, Arakawa J et al (1998) Surgical/tourniquet pain accelerates blood coagulability but not fibrinolysis. Br J Anaesth 80:460–463
41. Koopman MM, Prandoni P, Piovella F et al (1996) Treatment of venous thrombosis with intravenous unfractionated heparin administered in the hospital as compared with subcutaneous low-molecular-weight heparin administered at home. The Tasman Study Group. N Engl J Med 334:682–687
42. Kuipers S, Schreijer AJ, Cannegieter SC et al (2007) Travel and venous thrombosis: a systematic review. J Intern Med 262:615–634
43. Lewis HD Jr, Davis JW, Archibald DG et al (1983) Protective effects of aspirin against acute myocardial infarction and death in men with unstable angina. Results of a Veterans Administration Cooperative Study. N Engl J Med 309:396–403
44. Locker T, Goodacre S, Sampson F et al (2006) Meta-analysis of plethysmography and rheography in the diagnosis of deep vein thrombosis. Emerg Med J EMJ 23:630–635
45. Maletis GB, Inacio MC, Reynolds S et al (2012) Incidence of symptomatic venous thromboembolism after elective knee arthroscopy. J Bone Joint Surg Am 94:714–720
46. Marlovits S, Striessnig G, Schuster R et al (2007) Extended-duration thromboprophylaxis with enoxaparin after arthroscopic surgery of the anterior cruciate ligament: a prospective, randomized, placebo-controlled study. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 23:696–702
47. Masuda EM, Kistner RL, Musikasinthorn C et al (2012) The controversy of managing calf vein thrombosis. J Vasc Surg 55:550–561
48. Mauck KF, Froehling DA, Daniels PR et al (2013) Incidence of venous thromboembolism after elective knee arthroscopic surgery: a historical cohort study. J Thromb Haemost: JTH 11:1279–1286
49. Michot M, Conen D, Holtz D et al (2002) Prevention of deep-vein thrombosis in ambulatory arthroscopic knee surgery: a randomized trial of prophylaxis with low-molecular weight heparin. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 18:257–263
50. Morris RJ, Woodcock JP (2004) Evidence-based compression: prevention of stasis and deep vein thrombosis. Ann Surg 239:162–171
51. Navarro-Sanz A, Fernandez-Ortega JF (2004) Fatal pulmonary embolism after knee arthroscopy. Am J Sports Med 32:525–528
52. Roth P (1995) Thromboembolieprophylaxe bei ambulant durchgefurten arthroskopischen Meniskusoperationen. Orthop Prax 5:345–348
53. Pierson S, Pierson D, Swallow R et al (1983) Efficacy of graded elastic compression in the lower leg. JAMA 249:242–243
54. Ramos J, Perrotta C, Badariotti G et al (2008) Interventions for preventing venous thromboembo-

lism in adults undergoing knee arthroscopy. Cochrane Database Syst Rev 8(4):CD00529

55. Righini M (2007) Is it worth diagnosing and treating distal deep vein thrombosis? J Thromb Haemost: JTH 5:55–59
56. Robertson L, Kesteven P, Mccaslin JE (2015) Oral direct thrombin inhibitors or oral factor Xa inhibitors for the treatment of deep vein thrombosis. Cochrane Database Syst Rev (6):CD010956
57. Sakr Y (2015) What's new about heparin-induced thrombocytopenia type II. Intensive Care Med. doi:10.1007/s00134-015-3811-4, Epub ahead of print
58. Saltzman EW, Hirsh J (1982) Prevention of venous thromboembolism. In: Coleman RW (ed) Hemostasis and thrombosis. Lippincott, New York, p 986
59. Sampson FC, Goodacre SW, Thomas SM et al (2007) The accuracy of MRI in diagnosis of suspected deep vein thrombosis: systematic review and meta-analysis. Eur Radiol 17:175–181
60. Schellong SM (2007) Distal DVT. Worth diagnosing? Yes. J Thromb Haemost: JTH 5:51–54
61. Schippinger G, Wirnsberger GH, Obernosterer A et al (1998) Thromboembolic complications after arthroscopic knee surgery. Incidence and risk factors in 101 patients. Acta Orthop Scand 69:144–146
62. Schreijer AJ, Cannegieter SC, Meijers JC et al (2006) Activation of coagulation system during air travel: a crossover study. Lancet 367:832–838
63. Sherman OH, Fox JM, Snyder SJ et al (1986) Arthroscopy – "no-problem surgery". An analysis of complications in two thousand six hundred and forty cases. J Bone Jt Surg American volume 68:256–265
64. Siau K, Davies A, Laversuch CJ (2010) Is there still a role for computerized strain gauge plethysmography in the assessment of patients with suspected deep vein thrombosis? QJM 103:259–264
65. Stringer MD, Steadman CA, Hedges AR et al (1989) Deep vein thrombosis after elective knee surgery. An incidence study in 312 patients. J Bone Joint Surg British volume 71:492–497
66. Struijk-Mulder MC, Ettema HB, Verheyen CC et al (2013) Deep vein thrombosis after arthroscopic anterior cruciate ligament reconstruction: a prospective cohort study of 100 patients. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29:1211–1216
67. Sun Y, Chen D, Xu Z et al (2014) Incidence of symptomatic and asymptomatic venous thromboembolism after elective knee arthroscopic surgery: a retrospective study with routinely applied venography. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 30:818–822
68. Sun Y, Chen D, Xu Z et al (2014) Deep venous thrombosis after knee arthroscopy: a systematic review and meta-analysis. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 30:406–412
69. Thomas SM, Goodacre SW, Sampson FC et al (2008) Diagnostic value of CT for deep vein thrombosis: results of a systematic review and meta-analysis. Clin Radiol 63:299–304
70. Wells PS, Forgie MA, Rodger MA (2014) Treatment of venous thromboembolism. JAMA 311:717–728
71. Wells PS, Lensing AW, Davidson BL et al (1995) Accuracy of ultrasound for the diagnosis of deep venous thrombosis in asymptomatic patients after orthopedic surgery. A meta-analysis. Ann Intern Med 122:47–53
72. Wille-Jorgensen P, Jorgensen LN, Crawford M (2005) Asymptomatic postoperative deep vein thrombosis and the development of postthrombotic syndrome. A systematic review and meta-analysis. Thromb Haemost 93:236–241
73. Williams JS, Hulstyn MJ, Fadale PD et al (1995) Incidence of deep vein thrombosis after arthroscopic knee surgery: a prospective study. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 11:701–705
74. Wirth T, Schneider B, Misselwitz F et al (2001) Prevention of venous thromboembolism after knee arthroscopy with low-molecular weight heparin (reviparin): results of a randomized controlled trial. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 17:393–399
75. Wittkowsky AK (2001) Drug interactions update: drugs, herbs, and oral anticoagulation. J Thromb Thrombolysis 12:67–71
76. Wood RC 3rd, Stewart DW, Slusher L et al (2015) Retrospective evaluation of postoperative bleeding events in patients receiving rivaroxaban after undergoing total hip and total knee arthroplasty: comparison with clinical trial data. Pharmacotherapy 35(7):663–9
77. Ye S, Dongyang C, Zhihong X et al (2013) The incidence of deep venous thrombosis after arthroscopically assisted anterior cruciate ligament reconstruction. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29:742–747
78. Zierler BK (2004) Ultrasonography and diagnosis of venous thromboembolism. Circulation 109:I9–I14

11

Technical Considerations for Patellar Tendon Harvest

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11.1 Introduction

The bone-patellar tendon-bone (BTB) autograft and the hamstring tendon autograft are the most frequently used grafts in anterior cruciate ligament reconstruction (ACLR) [52, 69]. The patellar tendon technique is most frequently used in the United States [52], whereas the hamstring tendon technique is more common in Europe [26, 69]. In the late 1980s and early 1990s, the patellar tendon technique was considered as the gold standard, and this technique provided reliable results in stability and return to sports. However, donor-site morbidities were frequently reported and led to a shift toward hamstring tendon procedures and allografts in the early to mid-1990s [61]. Many surgeons were impressed with the seemingly easier recovery that occurred in the early phases after surgery using hamstring and cadaveric grafts. With a wave of enthusiasm for the hamstring graft, many surgeons believed that, compared to BTB autograft, hamstring tendons were just as successful but with lower complication rates and lower donor-site morbidity [61].

Over the last 10 years, many systematic reviews and meta-analyses assessing differences in graft failure, knee stability, and complications between both techniques have been published [11, 26, 30, 43, 44, 84, 93, 95]. Although most meta-analyses of randomized clinical trials did not show differences in graft failure between both techniques, some of these studies reported a tendency toward a higher failure rate with the hamstring tendon technique [11, 44, 93]. More recently, registries from Scandinavia and Kaiser Permanente confirmed this tendency reporting higher re-rupture rates with hamstring tendons [49, 68, 75]. Personal experience from one of the authors (AW) shows that in professional footballers the re-rupture using hamstring tendons is approximately double that of patellar tendons (see below).

Major problems that were reported with patellar tendon graft harvesting were related to donor-site morbidity. These included but were not limited to anterior knee pain and kneeling pain [11, 43, 44, 93] and loss of extension [11, 43]. However, this situation has improved to the extent that the donor-site morbidity is much lower than the morbidity reported in the 1980s

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and 1990s. In this book chapter, we will discuss the technical considerations that have contributed to this lower morbidity. Patient selection, technical considerations for BTB autograft harvest, and rehabilitation are discussed.

11.2 Patient Selection

Good results can generally be obtained with all graft types. Certain patients will benefit from some grafts more than others. For the modern soft tissue knee surgeon, we would suggest that a familiarity with using a variety of graft types is appropriate rather than always using the same graft.

11.2.1 Indications

In our opinion the patellar tendon graft is preferred in some specific patient groups, and these include (i) high-level footballers for the lower re-rupture rate; (ii) some amateur and professional high-level athletes for the lower re-rupture rate and to avoid weakening of the hamstrings (e.g., rock and wall climbing); (iii) high school (skeletally mature) and collegiate athletes, especially those with hyperlaxity, recurvatum, or increased tibial slope; (iv) revision cases from previous allograft or hamstring grafts; (v) patients who present with major laxity and malalignment, in whom perceived better stiffness of the patellar tendon and no hamstring weakening would seem to be advantageous; and (vi) patients with MCL laxity in whom ipsilateral hamstring harvest may reduce dynamic medial stability.

Many surgeons believe that graft strength is a major advantage of patellar tendon. Noyes and colleagues compared the maximum load-to-failure of different graft types and showed that patellar tendon graft is the strongest graft with strength of 168 % of the native ACL [65]. The semitendinosus, gracilis, and quadriceps tendons were significantly weaker (respectively, 70 %, 49 %, and 21 %). When the strength of the grafts was corrected for the width of the graft in mm, the patellar tendon graft was still stronger. However, as the authors of this study stated, the graft strength is irrelevant if graft fixation or healing to host bone is inadequate. Another advantage of patellar tendon ACL reconstruction is the faster bone-to-bone graft healing compared to tendon-to-bone healing in the first 6 weeks, and this can help high-level athletes in their early rehabilitation [48, 76, 88].

In patients with major preoperative knee laxity or generalized ligamentous laxity, the use of the patellar tendon would be logical because patellar tendon reconstruction has less residual laxity compared to hamstring tendon reconstruction. Several systematic reviews and meta-analyses showed that the anterior drawer, Lachman, and pivot shift tests had less laxity after ACL reconstructions with patellar tendon compared with the hamstring tendon [11, 30, 43, 44, 84, 93]. Therefore, we recommend BTB autograft for symptomatic ACL-deficient patients with major laxity.

11.2.2 Contraindications

Anterior knee pain was traditionally reported in 30–55 % of patellar tendon ACL reconstructions [37, 39, 47, 79] although a lower incidence was reported in older patients [71]. These rates have greatly reduced [5, 27, 62, 74] but are still more common with patellar tendon graft usage when compared to hamstring tendon grafts. Because of this high frequency, extensor mechanism pain prior to surgery is a relative contraindication of patellar tendon ACL reconstruction [56]. In addition, other graft types should be considered in patients with prior extensor mechanism injuries.

Another relative contraindication is repetitive kneeling for recreational, occupational, or religious reasons [48]. Some studies have reported postoperative problems with kneeling pain in up to 39 % [43], and meta-analyses have shown that kneeling pain is more common after patellar tendon harvest compared with hamstring tendon harvest [11, 43, 44, 93].

Patella alta or baja is also considered relative contraindications because they can result in a relatively long or short patellar tendon, respectively. A relatively long BTB autograft is more likely to result in graft-tunnel mismatch which can be addressed by a variety of techniques such as drilling a longer tibial tunnel, using an outside-in drilling or suspensory fixation on the femoral side, making a trough on the tibia for the bone block, or discarding the bone block on the tibial side altogether.

Furthermore, when harvesting the middle third of a patellar tendon of small width, which is usually seen in women of small stature, extensor mechanism problems can occur, and some authors have suggested to choose a different graft type [14]. However, these patients, due their short stature, have consequently small-diameter hamstring tendons, and the preference of the authors (AW and DN) is to use a BTB autograft in these patients or an allograft in an older and less active patient. The BTB autograft may only yield only an 8-mm wide graft, but this is preferable to using small hamstring tendons.

11.3 Patellar Tendon Harvest Technique

11.3.1 Skin Incision

Several causative factors are suggested for anterior knee pain of which two are specifically related to the skin incision: neurological injury of the infrapatellar branches of the saphenous nerve [27, 37, 72] and histologic changes of the donor-site healing process following decreased vascularity of the remaining two-thirds of the patella and patellar tendon [34, 42, 51, 66].

11.3.1.1 Innervation

The saphenous nerve descends at the medial side of the femur, and the infrapatellar branch of the saphenous nerve branches off toward the lateral side of the knee between the apex of the patella and media side of tibia [35]. The infrapatellar nerve is a sensory nerve that innervates the anterolateral skin of the knee. Several studies have shown that the infrapatellar nerve is susceptible to damage when incision is made close to the tibial tubercle and on the medial side of the joint as is performed with the classic single longitudinal incision in patellar tendon harvesting [2, 31, 32]. A cadaveric study reported the incidence of infrapatellar nerve damage with the classic incision in 59 % of the cases [72]. Kartus and coworkers [35] described the variations in anatomy of the infrapatellar nerve and found that 59 of 60 nerves (98 %) passed between the inferior pole of the patella and the tibial tubercle from medial to lateral. The nerve passed 30 mm (±13 mm [SD]) distal to the inferior pole of the patella and passed 27 mm (±13 mm [SD]) proximal to the tibial tubercle (Fig. 11.1), and this was confirmed in

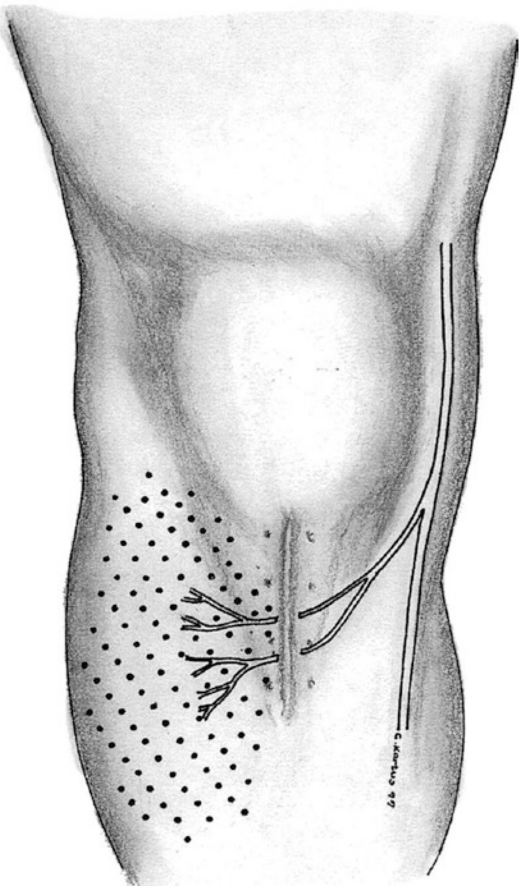

Fig. 11.1 The saphenous nerve descends on the medial side of the knee, and the infrapatellar branch crosses the midline between the patella and the tibial tubercle. In this figure two branches cross the midline, which is most commonly seen. The *dotted area* represents the cutaneous innervation of the infrapatellar branch of the saphenous nerve (Reprinted from Kartus et al. [36] with kind permission of *American Journal of Sports Medicine*)

another anatomical study [87]. In most cases (62 %) the nerve passed between these landmarks as superior and inferior branch although the infrapatellar nerve did not split into these two branches in some cases (25 %) or in even less cases had more than two branches (12 %).

Kartus and colleagues extensively described the correlation of anterior knee pain with iatrogenic damage of the infrapatellar branch of the saphenous nerve [35–38]. They retrospectively analyzed 604 patients who underwent BTB ACLR. At 2–5-year follow-up, they found correlations between limited range of motion, sensitivity loss, and anterior knee pain [37]. They concluded that loss of motion and loss of sensitivity were the two major factors affecting anterior knee pain and knee walking ability.

Moreover, studies have reported that injury of the infrapatellar nerve is also possible during portal incision of arthroscopic knee surgery [63, 87]. One study retrospectively assessed infrapatellar nerve damage during arthroscopy and found an incidence of 22.2 % [87], while another study found that in 8 of 20 cadavers (40 %), branches of the infrapatellar nerve were located at the position of the anteromedial portal [63]. Because the infrapatellar nerve moves distally with knee flexion, these studies recommended a horizontal incision technique with the knee in flexion to minimize the risk of nerve damage.

11.3.1.2 Different Incision Techniques

With the classic single-incision technique, a vertical skin incision is made medial to the tibial tubercle approximately 0.5 cm medial of the medial edge of the patellar tendon and is extended proximally for 6–8 cm [48, 96]. The length of the incision can be minimized by using the "mobile window" concept in which the wound can be moved proximally and distally with retraction to expose the tibial tuberosity and inferior patella. The authors' preferred technique is to make a paramedian longitudinal incision starting 0.5 cm medial to the inferior pole of the patella and extend distally to the level of the tendon insertion to the tibial tubercle (Fig. 11.2). At this point the incision is gently curved medially and distally for a further 1 cm to allow access for drilling of the tibial tunnel during ACLR. The overall length of the incision is usually between 4 and 6 cm. As mentioned above, we make full use of the "mobile window" concept, especially proximally, as the patella is mobile and can easily be delivered into the incision with the use of a Richardson-type retractor (Fig. 11.3).

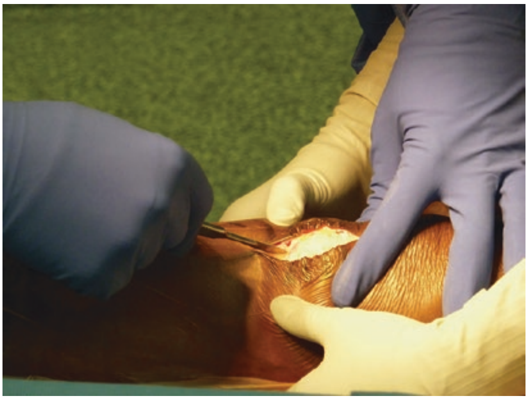

Fig. 11.2 The creation of a mobile window when making a limited incision from BTB harvest

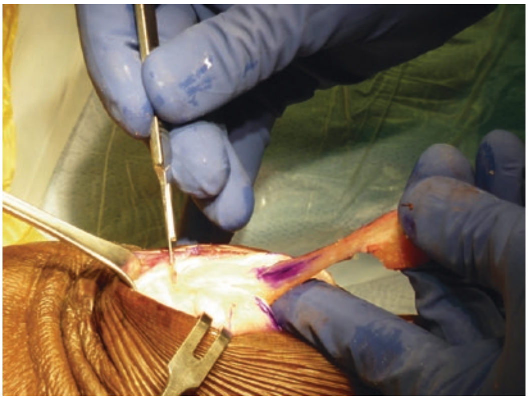

Fig. 11.3 Delivery of the patella into the mobile window with the use of a Richardson retractor and distal traction on the patella tendon

Because this incision can compromise the aforementioned innervation and also vascularization, several authors prefer a two-incision technique to prevent donor-site morbidity [5, 27, 35, 57, 62, 74]. This technique is usually performed with two vertical incisions (Fig. 11.4) [5, 27, 35, 57, 74] although also horizontal incisions can be used [62]. With the vertical incision technique, the tibial incision is located 1 cm medial of the

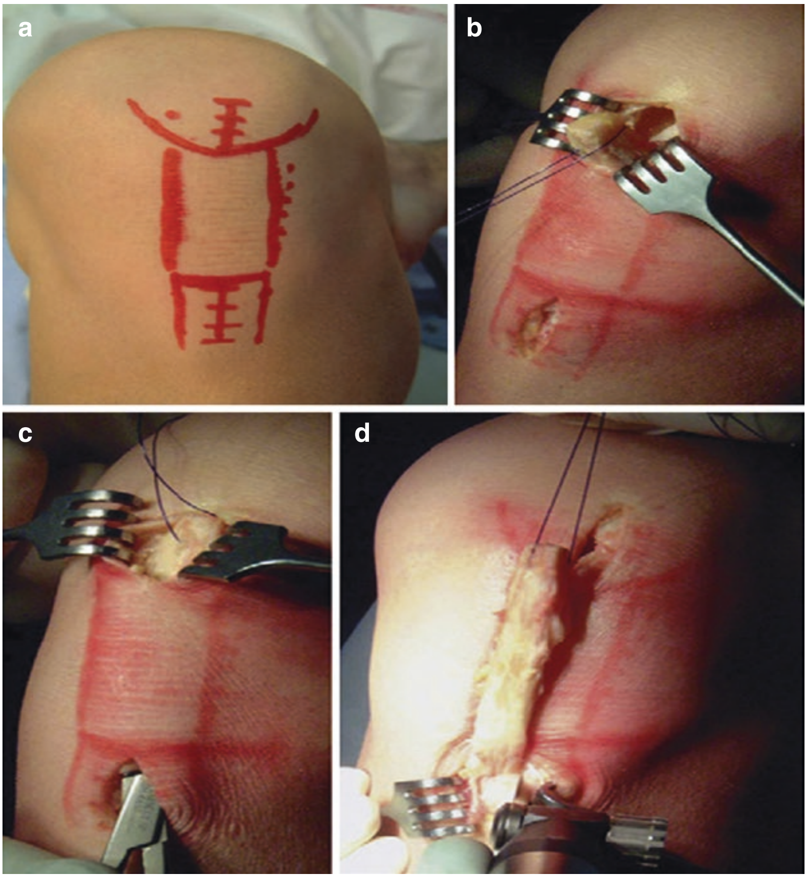

Fig. 11.4 The two-incision graft harvesting approach is shown. (**a**) The incision landmarks are drawn on the skin. (**b**) The patellar bone block with thread is harvested. (**c**) The paratenon is separated from the patellar tendon. (**d**) The patellar bone block and mid-third of the patellar tendon are drawn toward the tibial incision, and the graft is harvested via the tibial incision (Reprinted from Gaudot et al. [27] with kind permission of Elsevier)

tibial tubercle because the tibial tunnel drill guide will be positioned through this incision. A 25-mm vertical incision is then made centered on this position. The proximal incision is located at the center of the inferior pole of the patella and is extended proximal for 25 mm. In a cadaveric study, it was shown that with this technique the prevalence of iatrogenic infrapatellar nerve injury is only 5 % [35]. In addition, with this technique the average length of preserved paratenon is 27 mm (±11 [SD]), and this is important with its role in the vascularization of the patellar tendon.

Gaudot and colleagues compared the single-incision with the two-incision technique [27] and found that in the two-incision technique, patients reported significantly less anterior knee pain (19 % vs. 58 %), less cases of hypoesthesia (43 % vs. 89 %), and a smaller surface of hypoesthesia (4.9 cm^2 vs. 11.5 cm^2). In addition, Liden and colleagues assessed the incidence of anterior knee pain in patellar tendon harvesting with the vertical two-incision technique compared with hamstring tendon harvesting [45]. They found no significant difference in incidence of anterior knee pain between patellar tendon and hamstring tendon harvesting (32 % vs. 35 %, respectively).

11.3.2 Open Versus Arthroscopic

While good results of ACL reconstruction have been published using both open and arthroscopic ACLR [1, 15], we would strongly advise against the traditional open procedure of ACL reconstruction using BTB autograft. With the open procedure, the fat pad is excised in order to access the joint through the patellar tendon defect. The fat pad plays an important role in vascularity of both the patellar tendon and the patella. Moreover, the fat pad is highly innervated and is thought to

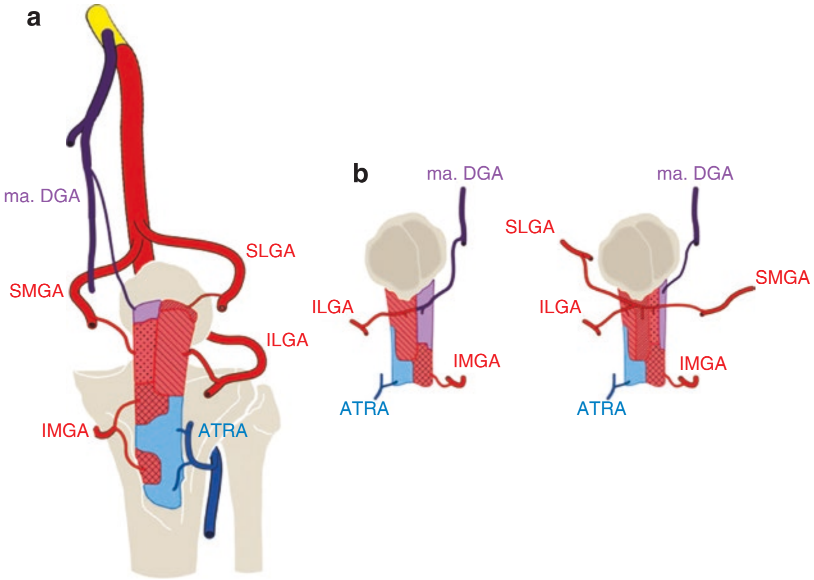

Fig. 11.5 The vascular supply of the patellar tendon is shown, (**a**) indicates the anterior surface of the patellar tendon, and (**b**) shows the two most common varieties of arterial supply of the posterior surface. Ma. *DGA* indicates muscular-articular part of descending genicular artery, *SMGA* superior medial genicular artery, *SLGA* superior lateral genicular artery, *IMGA* inferior-medial genicular artery, *ILGA* inferior-lateral genicular artery, *ATRA* ascending tibial recurrent artery (Reprinted from Pang et al. [66] with kind permission of permissions@wiley.com)

be a major source of pain [12, 22]. The fat pad has a great tendency to scar, which interferes with its ability to move and deform during knee motion. The scarring process can lead to contracture of the patellar tendon and subsequent patella baja. The inability of a scarred fat pad to move out of the anterior knee recess during knee extension can cause a fixed flexion deformity. Other good reasons to prefer an arthroscopic technique is the improved ability in identifying the appropriate position for the femoral tunnel.

11.3.2.1 Vascularity

Some authors have suggested that the decreased vascularity of the remaining patellar tendon can cause anterior knee pain, extension deficits, and patellar tendon ruptures [13, 27, 51, 66]. The patellar tendon is thought to have three major sources of blood supply [66]. The antero-proximal part of the tendon is mainly vascularized by the inferior-lateral genicular artery, and the antero-distal part is vascularized by an anastomotic arch of the anterior tibial recurrent artery and the inferior-medial genicular artery. Posteriorly, the patellar tendon is vascularized by the retropatellar anastomotic arch, which is located in the fat pad (Fig. 11.5). The importance of the role of the fat pad in patella tendon vascularization was previously described [66, 83]. Furthermore, it was shown that the paratenon, a sheath surrounding the patellar tendon, plays an important role in vascularization of the patellar tendon [66, 77, 83, 92]. Therefore multiple authors have proposed preservation of the paratenon during BTB autograft harvest [3, 35, 40, 54, 66, 77]. We make a longitudinal incision in the paratenon, in the central aspect of the patella tendon with a 15 blade. Medial and lateral flaps are elevated, and the longitudinal incision is extended proximally and distally with Metzenbaum scissors, protecting the underlying tendon (Fig. 11.6). At the end of the procedure, the paratenon is closed with a running Krakow-type suture using 2-0 Vicryl.

Other authors have suggested that decreased vascularity of the remaining patella could contribute to anterior knee pain [28, 42]. The main vascularization of the patella is from

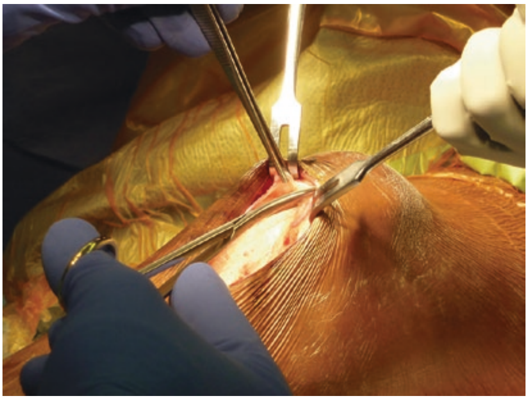

Fig. 11.6 Division and preservation of the paratenon

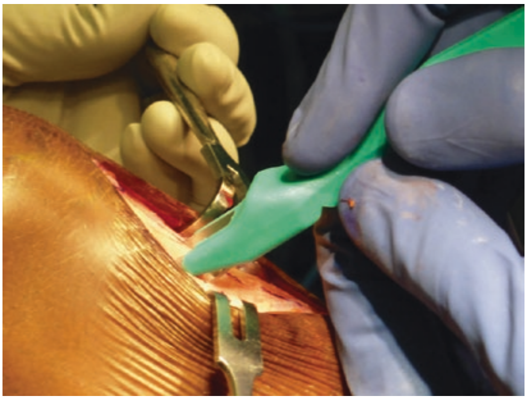

Fig. 11.7 Utilization of a double 10-mm blade to harvest the patella tendon

inferomedial (80 %), whereas vascularization from inferolateral (15 %) or inferior (5 %) is less common [42]. This finding has recently been confirmed by Jones and colleagues [34]. They assessed the vascularization of the patella before and after BTB autograft harvest in cadaveric knees and found that the vascularization of the patella decreased by 31 % (range 7–70 %) after tendon harvest. They suggested further clinical studies are needed to assess the relationship between patellar devascularization and anterior knee pain.

11.3.3 Patellar Tendon Incision

The incisions in the patella are made longitudinally to allow for the harvest of the central one-third of the patellar tendon. There are also reports of good results with harvest of the medial one-third of the tendon [50]. One of the major downsides of using the medial patellar third is postoperative maltracking of the patella to the lateral side [20] and subsequent alteration of patellofemoral contact pressure [17].

Before the patellar tendon is incised, the width should be measured. The width of the patellar tendon is on average 32 mm [9], and a tendon width of 10 or 11 mm is appropriate for BTB ACLR. Although it seems logical to use a larger part when the tendon is significantly wider than 30 mm, we recommend to not use a graft wider than 10–11 mm since this makes the graft impingement more likely [86]. Once the central one-third of the patellar tendon is measured, the width of the patellar tendon and the tendon-bone junctions should be marked with ink.

Two different techniques can be used for the incisions into the patellar tendon incision. One of the authors (AW) makes two single incisions with a scalpel, while the other author (DN) prefers to use a double-blade harvester (Fig. 11.7) [56]. This tendon harvester has two parallel scalpel blades, which ensure a uniform graft width from proximal to distal. Reliable results can be achieved with the two single incisions, but care should be taken to make parallel incisions to prevent variability in the width of the graft. This risk is increased when the patellar tendon is harvested with two skin incisions. In this case, scissors could be used within the paratenon to carefully extend the incision.

A few technical tips should be considered. First of all, the paratenon should be separated from the tendon and preserved as much as possible since the paratenon provides blood supply to the remaining patellar tendon [66, 77, 83, 92]. Secondly, there must be strict attention to preservation of the underlying fat pad, especially at its proximal aspect where it attaches to the inferior patella and vascularizes the patellar tendon [66, 77, 83] and the patella [34, 42]. Perforation of the fat pad proximally will also result in fluid extravasation during the subsequent arthroscopic procedure, compromising visualization. Finally, the order of incising the patellar tendon and bone block is important. When the bone blocks are sawn first and subsequently the patellar tendon is incised, it is easier to misalign the tendon and bone blocks' edges [56]. It is safer to make the tendon incisions first and then match the edges of the bone blocks to them.

11.3.4 Bone Block Harvesting

There are some important technical considerations for bone block harvesting. First of all, saw cuts should be angled at 45–60° in order to create trapezoid-shaped bone blocks. Matava and colleagues analyzed the cross-sectional area and the ratio of the bone block diameter to the tunnel diameter with triangle, rectangle, trapezoidal, and square cross-sectional blocks [53]. They found that a trapezoidal bone block had a large surface area in the tunnel and better contact with a curved surface, which optimizes bone-to-bone healing. They also reported that using a trapezoidal bone block enabled using a smaller tunnel for the graft when compared to a square cross-sectional block. If the bone block is not the correct shape, it can easily be trimmed on the back table. In primary reconstructions usually a 9- or 10-mm bone block is sufficient.

11.3.4.1 Tibial Bone Block

With lateral retraction of the skin, the distal tendon attachment site can be visualized since the skin incision is 1 cm medial to the center of the tibial tubercle. It is essential to identify the tendon insertion point of the patella into the tibia. Through one of the tendon incisions, this can be identified, and from this point the length of the bone block can be measured distally. The usual tibial bone block length is approximately 25 mm long and is marked out using electrocautery or a knife. An oscillating saw blade is then used to make two parallel longitudinal cuts. The saw blade is angled slightly by approximately 10–20°. The cuts are started at the proximal end of the tibial tubercle and extended distally for 25 mm. A horizontal saw cut is performed to connect the two vertical cuts (Fig. 11.8). It is important for the edges of the bone block to match up with the tendon or else some of the tendon will lack bony insertion [56]. A small osteotome is then used to lever the bone block out of place. Hammering of the osteotome should never be necessary and runs the risk of causing fractures. The graft is then elevated from the fat pad with sharp dissection, and the deep surface of the bone block is trimmed using bone nibblers and sized (usually 10 mm). The bone trimmed from the bone block is saved and used to graft the patellar bone defect later. If the cancellous bone here is excessively soft then, rather than removing it, it can be pressed by using pliers to harden the bone block.

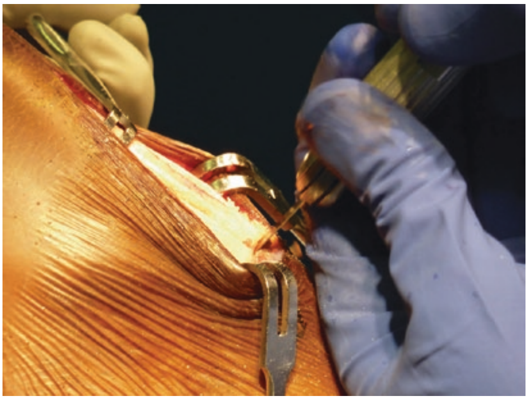

Fig. 11.8 Making the horizontal cut during harvest of the tibial tubercle bone block

11.3.4.2 Patellar Bone Block

The desired patellar block is marked out with ink or a knife. The width of the block is usually the same as the width of the harvested tendon and tibial tubercle bone block. In cases where the patella is small, the patella bone block may have to be downsized. A 10-mm saw is used for the two vertical medial and lateral cuts, and attention should be paid only to cut the cortex with the oscillating blade. The saw is angled at 45°. Some surgeons attach a depth stop to the saw blade to prevent differences in depth of drilling [56]. The depth stop aims to prevent differences in depth of sawing and therefore minimize the risk of producing points of stress concentration ("stress risers") and subsequent patellar fractures. The depth stop will also prevent injury to the retropatellar surface

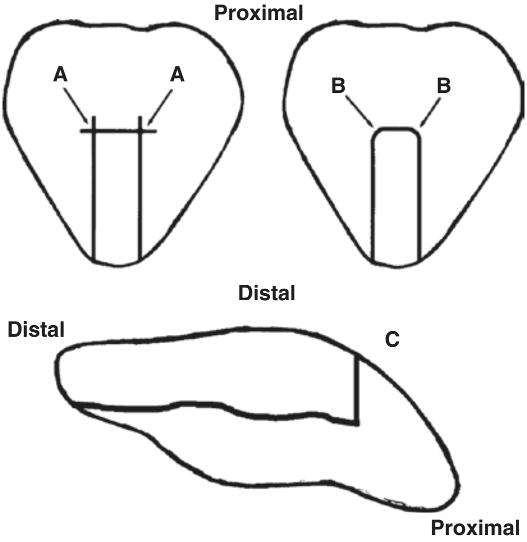

Fig. 11.9 The patella is shown with several cutting techniques. In example (**a**) the corners of the vertical cuts are overcut by the horizontal cut, and this can lead to stress risers and patella fractures. Example (**b**) shows the correct method of cutting the corners with the aid of a motorized burr. (**c**) Shows the depth of the vertical cuts and the horizontal cut and no overcutting is seen (Reprinted from [56]) with kind permission of Lippincott Williams & Wilkins)

from inadvertent very deep sawing. Similar attention should be paid to the horizontal cut joining the two vertical cuts. A 5-mm saw is used for the transverse cut to connect both vertical cuts. Care must be taken to use the saw to simply connect the vertical cuts because "cross-hatching" increases the risk of patellar fractures (Fig. 11.9) [56].

The graft is then pulled anteriorly and the 5-mm saw is inserted posteriorly to the patellar tendon insertion, and the saw is used to cut the bone block out in the coronal plane (Fig. 11.10). Usually the bone plug separates and using this method will ensure minimal bone resection from the patella. If required, soft tissue connections have to be divided, and inserting a small osteotome along the posterior aspect of the bone block and along the vertical cuts will help separate the block (Fig. 11.11). Hammering should not be necessary with the correct technique since this could cause fractures.

The graft is then taken to the back table and laid out on a graft prep station. The bone blocks

Fig. 11.10 Patella bone block being undercut to minimize bone loss and articular surface penetration

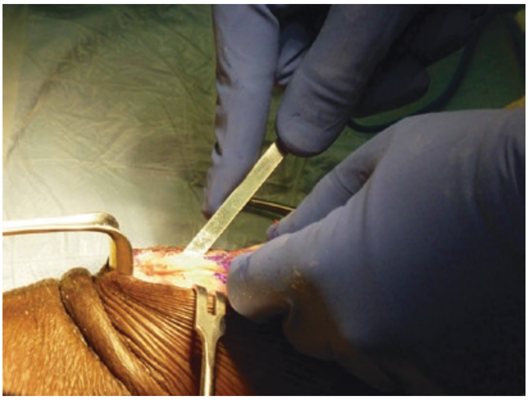

Fig. 11.11 Careful use of osteotome to lever out the patella bone block

are first trimmed to the planned diameter (usually 9–11 mm) and length. Either rongeurs or cylindrical crimpers can be used for this task. Sizers are used to ensure accurate sizing of the bone blocks (Fig. 11.12). One of the authors (DN) prefers to use the tibial tubercle bone block in the femur due to the increased offset between the tendon and bone at the tibial tubercle insertion and hence potentially less damage to the graft when inserting the femoral interference screw. The length of this block is made to between 20 and 23 mm. The bone-tendon junction is marked with blue ink to aid the surgeon during the subsequent ACLR, as a guide to ensure that the graft has bottomed out in the femoral socket. Two equally spaced drill holes are made with a Keith needle, with the proximal hole being 5 mm from

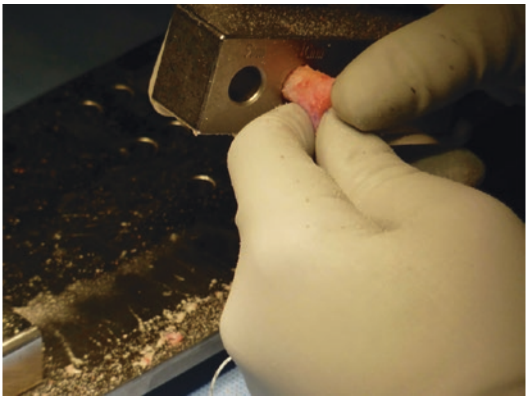

Fig. 11.12 Graft sizing is being performed to ensure easy passage of graft into tunnels during ACLR

Fig. 11.13 The final BTB graft construct

the tip of the bone block to allow for maximal control when guiding the bone block into the femoral socket. The tip is also “bulleted” to aid with graft passage. Subsequently, #5 Ethibond (Excel Ethicon, Somerville, NJ, USA) or #2 FiberWire (Arthrex, Naples, FL, USA) sutures are passed through these drill holes.

The patella bone block is then fashioned to the planned diameter and length (usually 25 mm). Three equally spaced drill holes are made with a Keith needle, and sutures are passed as done with the previous bone block. The holes are made obliquely across the bone block, and the bony surface that is devoid of drill holes is marked with blue ink. This guides the surgeon to place the tibial interference screw along this surface, thereby preventing damage to the sutures (Fig. 11.13). The final construct is then wrapped up in a saline-soaked gauze, placed in a kidney basin and inserted into a sterile clear bag to avoid contamination.

11.3.5 Tunnel Length

We tend to drill the femoral socket approximately 2 mm longer than the bone block length. This allows the potential problem of buildup of bony debris in the tunnel that would block adequate seating of the graft. With long tendons we occasionally drill 5 mm longer to allow some recessing of the graft if the tibial tunnel is not adequately long.

To calculate the length of the tibial tunnel, the length of the patellar tendon graft from the base of the femoral bone block to the tip of the tibial bone block should be measured. This graft occupies the intra-articular portion plus that in the tibial tunnel. Assuming an intra-articular graft length of 25–30 mm, depending on patient size, the required tibial tunnel desired length can easily be calculated. This calculation approximates very well and should prevent large graft-tunnel mismatches. Most modern ACL tibial aiming guides help the surgeon determine the required angle of drilling for the tibial tunnel in order to establish a tunnel of the appropriate length.

11.3.6 Graft Insertion

Before the graft is inserted, the soft tissue around the external aperture of the tibial tunnel must be cleared to prevent resistance on the graft as it is pulled into place. The sutures of the femoral bone block are tensioned so that they are all under equal tension. A steady traction force is applied and the femoral bone plug enters the external aperture of the tibial tunnel. If it catches here, applying further tension is rarely appropriate. Often the plug can be manipulated with a clamp and pushed into the tunnel. Usually the traction is applied with the knee at 90°, and as a result, when the bone plug emerges into the joint cavity, it does so at a steeper angle than the sutures going through the joint to the femoral tunnel. This will tend to rotate the bone plug at the proximal end of the tibial tunnel and may cause jamming. To overcome this the knee is simply extended so that the line of the bone block is parallel to the sutures. When this does not resolve the problem, an arthroscopic hook can be used to put traction within the joint to pull the bone plug into the joint cavity. The bone block is then free to be pulled up to the femur. The arthroscopic hook is also useful when directing the bone block into the femoral socket, particularly when it has been created by anteromedial portal drilling, and is not collinear with the tibial tunnel. As long as the calculation of length is correct, as the tip of the femoral bone plug engages the aperture of the femoral tunnel, the tibial bone plug will be close to the external aperture of the tibial tunnel. The graft is then pulled into place before fixation with interference screws.

11.3.7 Graft-Tunnel Mismatch

A graft-tunnel mismatch is still reported in 13–26 % of primary cases, and in most of these cases, the graft is too long compared to the tunnel [78, 91]. It is commonly seen when a hamstring graft ACL reconstruction is revised to tendon BTB ACLR using the same tibial tunnel. Several options are proposed to deal with this problem and mainly depend on the size of the mismatch. Some authors suggested using a cutoff of 12 mm to evaluate a mismatch being rather small or large [94].

When the mismatch is noted before graft insertion and the mismatch is smaller than 12 mm of excess length, it is suggested to externally rotate the block approximately two complete revolutions which results in 25 % graft shortening [4]. Also having a femoral tunnel longer than the femoral bone block will allow some recessing of the graft into the femur to take up length.

If after graft insertion a relatively small mismatch is noted with some of the tibial bone block protruding from its tunnel with a minimum of 15 mm of bone block left within the tibial tunnel and good bone quality, the protruding portion of bone block can simply be excised after fixation with an interference screw. This screw will pass across the bone block but also fix the soft tissue. It is therefore important to use an interference screw with soft thread to prevent the risk of damaging the graft. If there is a suture remaining in the bone block within the tibia, this can be used to provide supplementary fixation by means of a posting screw or suture anchor.

If the mismatch is greater, a "free bone block technique" can be used in which the bone block is removed from the tendon, the free end of the tendon is whipstitched, and the bone block is slid alongside the tendon in the tibial tunnel and secured with an interference screw while maintaining tension on the intratendinous sutures [91, 94]. The bone block can also simply be removed, thereby giving a graft with a single bone block at the femoral end and soft tissue to bone fixation at the tibial end. Another option is rolling the distal block back onto the tendon and suturing the block to the tendon thereby shortening the graft by the length and thickness of the bone block [33]. With a really large mismatch, a bony trough can be created in the tibia distal to the external aperture of the tibial tunnel. The bone block of the distal graft can be recessed into it and fixed with staples.

If the graft is too short, it is important to first ensure that the femoral bone block has not been pulled in excessively, by checking the tendon-bone junction arthroscopically. The junction should usually be at the femoral tunnel aperture into the joint. It is helpful to view this arthroscopically by marking the tendon-bone junction with blue ink during graft preparation. If the graft is in the correct position within the femoral tunnel and the mismatch is a few millimeters, then the graft can be tensioned with the sutures and the screw can be introduced carefully into the tibia. The safest option is to place the screw away from the tensioning suture to avoid cutting the sutures as previously described. If the sutures fail, there are three scenarios. If at the moment of suture failure most of the screw is already inserted and good fixation is noticed, a prominent screw can be accepted with a view to early removal at 12 weeks postoperatively if needed. If the screw has barely been inserted and fixation is inadequate, the tibia overlying the tunnel has to be "de-roofed" to expose the graft for retrieval. In a case of a large mismatch and a graft up the tibial tunnel, a decision can be made not to use interference screw fixation and to tie the tibial bone block sutures over a posting screw or an anchor. In worst-case scenarios, a different graft should be considered [94].

11.3.8 Grafting of Bone Defects

Fragments of bone removed from the bone blocks and drilling are impacted in the patellar bone defect. When harvesting the tibial tubercle bone, we deliberately harvest the graft with a V-shape at the apex deep to provide good amount of cancellous bone for later bone grafting. The small fragments of bone from the drilling provide a "grout" to hold the larger fragments in place. The scrupulous collection of these bone chips is usually enough to fill the tibial defect as well. If this is not sufficient, an osteotome can be used to elevate cancellous bone from deep in the tibial harvest site to fill the defect. While the patellar bone defect needs to be filled flushed with the surface of the patella, it is important to realize that the tibial defect only needs to be filled as far as the anterior extent of bone and not up to the anterior extent of the tendon.

One of the authors (DN) routinely uses a "coring" reamer (Arthrex, Naples, FL, USA) when drilling the tibial tunnel. This particular reamer preserves the reamed tibial bone as a cylinder within the reamer, which can then be removed and fits almost perfectly into the patellar bony defect (Figs. 11.14 and 11.15).

Fig. 11.14 The cylindrical "core" of bone that is generated from a "coring" reamer after drilling of the tibial tunnel

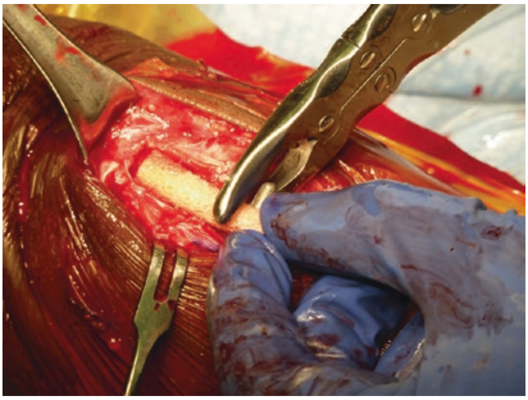

Fig. 11.15 The "core" of bone usually fits perfectly into the patellar bone defect

11.3.9 Patellar Tendon Closure

Historically, the patellar tendon was closed after patellar tendon grafting, but authors showed that, after complete closure, the patellar tendon is shortened by 10 % in 73 % of the cases [25] and this was thought to be correlated with patella baja, anterior knee pain, and crepitus [70, 89]. However, some authors questioned this shortening [58] and others showed that the patella defect could regenerate into a firm scar, and both findings led to a debate whether it was necessary to close the defect [8, 23, 46, 73].

Generally, there are three options regarding the management of the patellar tendon defect: (1) closure of both the patellar tendon and paratenon, (2) closure of the paratenon only, or (3) leaving both the tendon defect and paratenon unrepaired. A recent systematic review reported four randomized clinical trials that compared closure versus non-closure of the patellar tendon defect [24]. They found no differences regarding pain, range of motion, clinical outcome scores, and incidence of patella alta between both surgical procedures. One randomized clinical trial compared the effect of closure of the paratenon and bone grafting on patellar defect closure. Their results showed that closure of paratenon enhances healing of the patellar tendon defect and restores normal appearance of the tendon within 2 years [41]. Therefore, both closing and leaving the defect unrepaired are possible although it is advised to close the paratenon and thus optimize the vascularity and healing of the patellar tendon [48]. If the surgeon prefers to close the patellar tendon, this should be performed in 90° of knee flexion since this allows equal tension on the medial and lateral thirds of the tendon. Our preference is to close the defect with interrupted absorbable sutures [96].

Furthermore, some authors have suggested using platelet-rich plasma (PRP) to fill and regenerate the patellar tendon defect [16, 19, 64]. The use of PRP is a relatively new technique, and two randomized clinical trials showed that with PRP, the patellar tendon defect is smaller on MRI and less postoperative pain is reported. Although these techniques could have a role in the treatment of patellar tendon defects, these techniques are fairly new and further research is indicated.

11.4 Rehabilitation

Historically, crude rehabilitation, including long periods in casts, was a major cause of morbidity in the period when patellar tendon ACL reconstruction was associated with frequent extensor mechanism problems. There are some special considerations that should be taken into account with the use of patellar tendon autograft. The most important issue is achieving full active extension [80–82].

Accelerated rehabilitation protocols with full weight bearing, full ROM, early closed kinetic chain quadriceps exercises, and even return to play within 4 months are described in the literature [55]. Beynnon et al. compared accelerated versus non-accelerated rehabilitation programs following patellar tendon ACL reconstruction in a double-blind randomized clinical trial and found no differences in laxity, functional performance, proprioception, and thigh muscle strength at 1-year follow-up [10]. However, in order to prevent re-ruptures, we would not advocate a return to play before 6–9 months. Recovery of passive and active motion and full weight bearing are recommended in the immediate setting to reduce pain, arthrofibrosis, and muscle atrophy [55, 90]. The aforementioned faster bone-to-bone healing with the patellar tendon graft compared to tendon-to-bone healing in hamstring tendon graft plays a role in this consideration. Moreover, since anterior knee pain is a major complaint after patellar tendon reconstruction, it is reported that regaining of quadriceps control and full knee extension in the first few weeks after surgery are major indicators of preventing anterior knee pain [55, 80–82]. This includes intensive rehabilitation of the quadriceps mechanism with closed kinetic chain exercises within the first few weeks with a safe range of 0–45° or 0–60° of flexion [55, 90]. Flexion can be increased but is of secondary importance. Extension loss is frequently reported in reconstructions with the patellar tendon (11–13 % of cases) [29, 37, 67]. Although this extension loss is now uncommon in our experience, it is more common than in hamstring tendon reconstructions [11, 93].

Another important reason for full active extension is the prevention of fat pad scarring. The quadriceps, pulling through the patella and patellar tendon, would tend to stretch and compress the fat pad and prevent contractures. Most patients find it more comfortable to rest with the knee flexed around 10–20° since the fat pad has the most room in the anterior knee in this position. Without frequently getting full active extension, the fat pad will scar and become relatively rigid. As a result the fat pad cannot move out of the way, as it would normally, by the compression from articular surfaces and anterior horn advancement. This blocks knee extension. With a well-placed graft, there should be no fear of graft damage with knee motion and thus full early active and passive hyperextension and patellar glides should be performed to prevent fat pad scarring.

11.5 Dealing with Complications

11.5.1 Patellar Fractures

Patella fractures are a rare intra- or postoperatively complication in patellar tendon ACL reconstructions (0.4–1.3 %) [59, 60, 85]. Fractures are mostly the results of deep saw cuts, “cross-hatching” of the corners of vertical and horizontal cuts, or harvesting of a large patella bone block. Deep saw cuts in the patella can lead to vertical fractures and can be treated with fixation by two transverse screws and bone grafting of the defect. The first screw is placed proximal to the bone defect so that no excessive compression occurs. The second screw is then inserted at the level of bone graft. It is useful to wedge a piece of cortical bone into the bone defect to prevent the second screw compressing the site of the bone defect. This bone can be harvested from the tibial metaphysis. Harvesting grafts of excessive size and overcutting of corners can cause transverse fractures, which can be treated with a tension band wire after filling the bone defect with graft. Surgical treatment of displaced fractures and the conservative treatment of non-displaced fractures both have good results and only have a small effect on postoperative management [60, 85].

11.5.2 Patellar Tendon Ruptures

The incidence of patellar tendon ruptures is very low (0.18–0.25 %) [6, 59]. It would probably tend to occur at the proximal end of graft harvest with rough handling of the soft tissues or failure to centralize the graft harvest and thus leave a vulnerable and small medial or lateral band of tendon. If during surgery the patellar tendon is at significant risk, it can be reinforced in a similar way as treating a primary patellar tendon rupture. Full patellar tendon ruptures should be treated operatively in order to allow continuation of the rehabilitation program [59], but partial tears can be treated conservatively [7].

The preferred operative technique of one of the authors (AW) is, after direct repair of the ruptured tendon, to take the semitendinosus and gracilis, left attached to the tibia, upwards medial to the patellar tendon, then pass it through a transverse drill hole in the patella around its equator and finally guide it down lateral to the patellar tendon before fixation to the lateral tibia using either an interference screw or double staple technique buried under the tibialis anterior.

11.5.3 Persistent Anterior Knee Pain

In some cases, even with perfect surgical technique, patients report troublesome anterior knee pain. Firstly the cause needs to be identified. Radiographs, ultrasound scanning, MRI, and SPECT CT scanning can all be useful. Problems with bony healing can occur in the defect, but also occasionally small marginal fractures of the patella, close to the inferior region of bone graft harvest site, can occur. These are presumably small stress fractures related to abnormal loading on the soft tissues attached to them. The identification of the fragments can be difficult. Therefore SPECT CT with additional diagnostic injection of anesthetic under ultrasound control is useful. After identifying these fragments, the pain can be treated with their excision. Poor healing of the patellar donor site may require curettage and bone grafting. Steroid injections into this area are contraindicated as it is associated with patellar tendon rupture [18]. However, in the case of tendon healing problems, injection of PRP or sucrose (“prolotherapy”) has a place in treatment.

When surgical intervention is not indicated, it is essential to be sure that optimal physiotherapy has been undertaken. Full knee extension and quadriceps muscle control during rehabilitation can improve anterior knee pain [55, 82]. In addition, poor gluteal function will tend to lead to internal rotation of the hip and provide a valgus external rotation force at the knee during activity. This can lead to overload of the lateral patellofemoral joint and the superolateral fat pad [21], and since the fat pad is highly innervated, this could contribute to anterior knee pain [12]. If significant edema in the fat pad is seen on MRI, an injection with local anesthetic and steroids can be injected with ultrasound guidance, and this will likely reduce the symptoms. If the pain reduces, further muscle strengthening with physiotherapy will be easier and prevent recurrence of symptoms [21].

Conclusion

Modern equipment and improvements in surgical technique have considerably reduced the donor-site morbidity and complications associated with BTB autograft harvest for

ACLR. While anterior knee pain is still more frequent with BTB harvest than hamstring harvest, the difference is sufficiently small to preclude the use of the patellar tendon in situations where it may be considered the superior graft choice.

References

1. Arnold MP, Friederich NF, Muller W, Hirschmann MT (2013) From open to arthroscopic anatomical ACL-reconstructions: the long way round. A statement paper. Knee Surg Sports Traumatol Arthrosc 21(7):1478–1481. doi:10.1007/s00167-012-2029-z
2. Arthornthurasook A, Gaew-Im K (1988) Study of the infrapatellar nerve. Am J Sports Med 16(1):57–59
3. Atkinson TS, Atkinson PJ, Mendenhall HV, Haut RC (1998) Patellar tendon and infrapatellar fat pad healing after harvest of an ACL graft. J Surg Res 79(1):25–30. doi:10.1006/jsre.1998.5387
4. Auge WK 2nd, Yifan K (1999) A technique for resolution of graft-tunnel length mismatch in central third bone-patellar tendon-bone anterior cruciate ligament reconstruction. Arthroscopy 15(8):877–881
5. Beaufils P, Gaudot F, Drain O, Boisrenoult P, Pujol N (2011) Mini-invasive technique for bone patellar tendon bone harvesting: its superiority in reducing anterior knee pain following ACL reconstruction. Curr Rev Musculoskelet Med 4(2):45–51. doi:10.1007/s12178-011-9077-8
6. Benner RW, Shelbourne KD, Freeman H (2011) Infections and patellar tendon ruptures after anterior cruciate ligament reconstruction: a comparison of ipsilateral and contralateral patellar tendon autografts. Am J Sports Med 39(3):519–525. doi:10.1177/0363546510388163
7. Benner RW, Shelbourne KD, Freeman H (2013) Nonoperative management of a partial patellar tendon rupture after bone-patellar tendon-bone graft harvest for ACL reconstruction. J Knee Surg 26(Suppl 1):S123–S127. doi:10.1055/s-0032-1324810
8. Berg EE (1992) Intrinsic healing of a patellar tendon donor site defect after anterior cruciate ligament reconstruction. Clin Orthop Relat Res 278:160–163
9. Bernicker JP, Haddad JL, Lintner DM, DiLiberti TC, Bocell JR (1998) Patellar tendon defect during the first year after anterior cruciate ligament reconstruction: appearance on serial magnetic resonance imaging. Arthroscopy 14(8):804–809
10. Beynnon BD, Uh BS, Johnson RJ, Abate JA, Nichols CE, Fleming BC, Poole AR, Roos H (2005) Rehabilitation after anterior cruciate ligament reconstruction: a prospective, randomized, double-blind comparison of programs administered over 2 different time intervals. Am J Sports Med 33(3):347–359
11. Biau DJ, Tournoux C, Katsahian S, Schranz PJ, Nizard RS (2006) Bone-patellar tendon-bone autografts versus hamstring autografts for reconstruction of anterior cruciate ligament: meta-analysis. BMJ 332(7548):995–1001. doi:10.1136/bmj.38784.384109.2F
12. Bohnsack M, Meier F, Walter GF, Hurschler C, Schmolke S, Wirth CJ, Ruhmann O (2005) Distribution of substance-P nerves inside the infrapatellar fat pad and the adjacent synovial tissue: a neurohistological approach to anterior knee pain syndrome. Arch Orthop Trauma Surg 125(9):592–597. doi:10.1007/s00402-005-0796-4
13. Bonamo JJ, Krinick RM, Sporn AA (1984) Rupture of the patellar ligament after use of its central third for anterior cruciate reconstruction. A report of two cases. J Bone Joint Surg Am 66(8):1294–1297
14. Busam ML, Provencher MT, Bach BR Jr (2008) Complications of anterior cruciate ligament reconstruction with bone-patellar tendon-bone constructs: care and prevention. Am J Sports Med 36(2):379–394. doi:10.1177/0363546507313498
15. Cameron SE, Wilson W, St Pierre P (1995) A prospective, randomized comparison of open vs arthroscopically assisted ACL reconstruction. Orthopedics 18(3): 249–252
16. Cervellin M, de Girolamo L, Bait C, Denti M, Volpi P (2012) Autologous platelet-rich plasma gel to reduce donor-site morbidity after patellar tendon graft harvesting for anterior cruciate ligament reconstruction: a randomized, controlled clinical study. Knee Surg Sports Traumatol Arthrosc 20(1):114–120. doi:10.1007/s00167-011-1570-5
17. Chan KM, Qin L, Li CK, Hung LK, Tang CY, Rolf C (2000) Removal of the lateral or medial third of patellar tendon alters the patellofemoral contact pressure and area: an in vitro experimental study in dogs. Clin Biomech (Bristol, Avon) 15(9):695–701
18. Clark SC, Jones MW, Choudhury RR, Smith E (1995) Bilateral patellar tendon rupture secondary to repeated local steroid injections. J Accid Emerg Med 12(4): 300–301
19. de Almeida AM, Demange MK, Sobrado MF, Rodrigues MB, Pedrinelli A, Hernandez AJ (2012) Patellar tendon healing with platelet-rich plasma: a prospective randomized controlled trial. Am J Sports Med 40(6):1282–1288. doi:10.1177/0363546512441344
20. Dhillon MS, Mohan P, Nagi ON (2003) Does harvesting the medial third of the patellar tendon cause lateral shift of the patella after ACL reconstruction? Acta Orthop Belg 69(4):334–340
21. Dragoo JL, Johnson C, McConnell J (2012) Evaluation and treatment of disorders of the infrapatellar fat pad. Sports Med 42(1):51–67. doi:10.2165/11595680-000000000-00000
22. Dye SF (2005) The pathophysiology of patellofemoral pain: a tissue homeostasis perspective. Clin Orthop Relat Res 436:100–110
23. Frank CB, Jackson DW (1997) The science of reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am 79(10):1556–1576
24. Frank RM, Mascarenhas R, Haro M, Verma NN, Cole BJ, Bush-Joseph CA, Bach BR Jr (2015) Closure of

patellar tendon defect in anterior cruciate ligament reconstruction with bone-patellar tendon-bone autograft: systematic review of randomized controlled trials. Arthroscopy 31(2):329–338. doi:10.1016/j.arthro.2014.09.004

25. Fu FH, Bennett CH, Ma CB, Menetrey J, Lattermann C (2000) Current trends in anterior cruciate ligament reconstruction. Part II. Operative procedures and clinical correlations. Am J Sports Med 28(1):124–130
26. Gabler CM, Jacobs CA, Howard JS, Mattacola CG, Johnson DL (2015) Comparison of graft failure rate between autografts placed via an anatomic anterior cruciate ligament reconstruction technique: a systematic review, meta-analysis, and meta-regression. Am J Sports Med. doi:10.1177/0363546515584043
27. Gaudot F, Leymarie JB, Drain O, Boisrenoult P, Charrois O, Beaufils P (2009) Double-incision mini-invasive technique for BTB harvesting: its superiority in reducing anterior knee pain following ACL reconstruction. Orthop Traumatol Surg Res 95(1):28–35. doi:10.1016/j.otsr.2008.09.006
28. Gelfer Y, Pinkas L, Horne T, Halperin N, Alk D, Robinson D (2003) Symptomatic transient patellar ischemia following total knee replacement as detected by scintigraphy. Knee 10(4):341–345. doi:10.1016/s0968-0160(03)00026-7
29. Harner CD, Irrgang JJ, Paul J, Dearwater S, Fu FH (1992) Loss of motion after anterior cruciate ligament reconstruction. Am J Sports Med 20(5):499–506
30. Herrington L, Wrapson C, Matthews M, Matthews H (2005) Anterior cruciate ligament reconstruction, hamstring versus bone-patella tendon-bone grafts: a systematic literature review of outcome from surgery. Knee 12(1):41–50. doi:10.1016/j.knee.2004.02.003
31. Horner G, Dellon AL (1994) Innervation of the human knee joint and implications for surgery. Clin Orthop Relat Res 301:221–226
32. Hunter LY, Louis DS, Ricciardi JR, O'Connor GA (1979) The saphenous nerve: its course and importance in medial arthrotomy. Am J Sports Med 7(4):227–230
33. Jackson DW, Cohn BT, Morrison DS (1990) A new technique for harvesting the patella tendon in patients undergoing anterior cruciate ligament reconstruction. Orthopedics 13(2):165–167
34. Jones KJ, Lazaro LE, Taylor SA, Pardee NC, Dyke JP, Hannafin JA, Warren RF, Lorich DG (2015) Quantitative assessment of patellar vascularity following bone-patellar tendon-bone autograft harvest for ACL reconstruction. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-015-3510-2
35. Kartus J, Ejerhed L, Eriksson BI, Karlsson J (1999) The localization of the infrapatellar nerves in the anterior knee region with special emphasis on central third patellar tendon harvest: a dissection study on cadaver and amputated specimens. Arthroscopy 15(6):577–586. doi:10.1053/ar.1999.v15.015057001
36. Kartus J, Ejerhed L, Sernert N, Brandsson S, Karlsson J (2000) Comparison of traditional and subcutaneous patellar tendon harvest. A prospective study of donor site-related problems after anterior cruciate ligament reconstruction using different graft harvesting techniques. Am J Sports Med 28(3):328–335
37. Kartus J, Magnusson L, Stener S, Brandsson S, Eriksson BI, Karlsson J (1999) Complications following arthroscopic anterior cruciate ligament reconstruction. A 2–5-year follow-up of 604 patients with special emphasis on anterior knee pain. Knee Surg Sports Traumatol Arthrosc 7(1):2–8
38. Kartus J, Movin T, Karlsson J (2001) Donor-site morbidity and anterior knee problems after anterior cruciate ligament reconstruction using autografts. Arthroscopy 17(9):971–980. doi:10.1053/jars.2001.28979
39. Kleipool AE, van Loon T, Marti RK (1994) Pain after use of the central third of the patellar tendon for cruciate ligament reconstruction. 33 patients followed 2–3 years. Acta Orthop Scand 65(1):62–66
40. Koh E, Oe K, Takemura S, Iida H (2015) Anterior cruciate ligament reconstruction using a bone-patellar tendon-bone autograft to avoid harvest-site morbidity in knee arthroscopy. Arthrosc Tech 4(2):e179–e184. doi:10.1016/j.eats.2015.01.002
41. Kohn D, Sander-Beuermann A (1994) Donor-site morbidity after harvest of a bone-tendon-bone patellar tendon autograft. Knee Surg Sports Traumatol Arthrosc 2(4):219–223
42. Lazaro LE, Wellman DS, Klinger CE, Dyke JP, Pardee NC, Sculco PK, Berkes MB, Helfet DL, Lorich DG (2013) Quantitative and qualitative assessment of bone perfusion and arterial contributions in a patellar fracture model using gadolinium-enhanced magnetic resonance imaging: a cadaveric study. J Bone Joint Surg Am 95(19):e1401–e1407. doi:10.2106/JBJS.L.00401
43. Li S, Chen Y, Lin Z, Cui W, Zhao J, Su W (2012) A systematic review of randomized controlled clinical trials comparing hamstring autografts versus bone-patellar tendon-bone autografts for the reconstruction of the anterior cruciate ligament. Arch Orthop Trauma Surg 132(9):1287–1297. doi:10.1007/s00402-012-1532-5
44. Li S, Su W, Zhao J, Xu Y, Bo Z, Ding X, Wei Q (2011) A meta-analysis of hamstring autografts versus bone-patellar tendon-bone autografts for reconstruction of the anterior cruciate ligament. Knee 18(5):287–293. doi:10.1016/j.knee.2010.08.002
45. Liden M, Ejerhed L, Sernert N, Laxdal G, Kartus J (2007) Patellar tendon or semitendinosus tendon autografts for anterior cruciate ligament reconstruction: a prospective, randomized study with a 7-year follow-up. Am J Sports Med 35(5):740–748. doi:10.1177/0363546506298275
46. Liu SH, Hang DW, Gentili A, Finerman GA (1996) MRI and morphology of the insertion of the patellar tendon after graft harvesting. J Bone Joint Surg (Br) 78(5):823–826
47. Lund B, Nielsen T, Fauno P, Christiansen SE, Lind M (2014) Is quadriceps tendon a better graft choice than patellar tendon? a prospective randomized study. Arthroscopy 30(5):593–598. doi:10.1016/j.arthro.2014.01.012
48. Magnussen RA, DeAngelis JP, Spindler KP (2012) Bone-patellar tendon-bone autograft anterior cruciate ligament reconstruction. In: Scott WN (ed) Insall &

Scott surgery of the knee, 5th edn. Elsevier, Philadelphia, pp 385–392
49. Maletis GB, Inacio MC, Desmond JL, Funahashi TT (2013) Reconstruction of the anterior cruciate ligament: association of graft choice with increased risk of early revision. Bone Joint J 95-B(5):623–628. doi:10.1302/0301-620x.95b5.30872
50. Marimuthu K, Joshi N, Sharma M, Sharma CS, Bhargava R, Rajawat AS, Rangdal SS (2011) Anterior cruciate ligament reconstruction using the medial third of the patellar tendon. J Orthop Surg (Hong Kong) 19(2):221–225
51. Marumoto JM, Mitsunaga MM, Richardson AB, Medoff RJ, Mayfield GW (1996) Late patellar tendon ruptures after removal of the central third for anterior cruciate ligament reconstruction. A report of two cases. Am J Sports Med 24(5):698–701
52. Marx RG, Jones EC, Angel M, Wickiewicz TL, Warren RF (2003) Beliefs and attitudes of members of the American Academy of orthopaedic surgeons regarding the treatment of anterior cruciate ligament injury. Arthrosc J Arthrosc Relat Surg 19(7):762–770. doi:10.1016/s0749-8063(03)00398-0
53. Matava MJ, Shively RA, Anders JD (1996) Geometrical relationships between bone plug configuration and patellar tendon graft width. Am J Knee Surg 9(2):67–72
54. McCarthy MM, Hannafin JA (2014) The mature athlete: aging tendon and ligament. Sports Health 6(1):41–48. doi:10.1177/1941738113485691
55. McCarty LP III, Bach BR Jr (2005) Rehabilitation after patellar tendon autograft anterior cruciate ligament reconstruction. Tech Orthop 20(4):439–451
56. McGuire DA, Hendricks SD (2007) Anterior cruciate ligament reconstruction graft harvesting: pitfalls and tips. Sports Med Arthrosc 15(4):184–190. doi:10.1097/JSA.0b013e3181595bb6
57. McGuire DA, Hendricks SD (2008) Reconstructive knee surgery. In: Jackson DW (ed) Patellar tendon graft harvesting, Lippincott Williams and Wilkins, Philadelphia, pp 185–195
58. Meisterling RC, Wadsworth T, Ardill R, Griffiths H, Lane-Larsen CL (1993) Morphologic changes in the human patellar tendon after bone-tendon-bone anterior cruciate ligament reconstruction. Clin Orthop Relat Res 289:208–212
59. Milankov M, Kecojevic V, Rasovic P, Kovacevic N, Gvozdenovic N, Obradovic M (2013) Disruption of the knee extensor apparatus complicating anterior cruciate ligament reconstruction. Acta Chir Iugosl 60(2):13–21
60. Milankov M, Rasovic P, Kovacev N, Milovic M, Bojat V (2012) Fracture of the patella after the anterior cruciate ligament reconstruction. Med Pregl 65(11-12): 476–482
61. Miller SL, Gladstone JN (2002) Graft selection in anterior cruciate ligament reconstruction. Orthop Clin N Am 33(4):675–683
62. Mishra AK, Fanton GS, Dillingham MF, Carver TJ (1995) Patellar tendon graft harvesting using horizontal incisions for anterior cruciate ligament reconstruction. Arthroscopy 11(6):749–752
63. Mochida H, Kikuchi S (1995) Injury to infrapatellar branch of saphenous nerve in arthroscopic knee surgery. Clin Orthop Relat Res 320:88–94
64. Nakamura N (2013) Platelet-rich plasma added to the patellar tendon harvest site during anterior cruciate ligament reconstruction enhanced healing. J Bone Joint Surg Am 95(10):942. doi:10.2106/JBJS.9510.ebo450
65. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS (1984) Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. J Bone Joint Surg Am 66(3):344–352
66. Pang J, Shen S, Pan WR, Jones IR, Rozen WM, Taylor GI (2009) The arterial supply of the patellar tendon: anatomical study with clinical implications for knee surgery. Clin Anat 22(3):371–376. doi:10.1002/ca.20770
67. Passler JM, Schippinger G, Schweighofer F, Fellinger M, Seibert FJ (1995) Complications in 283 cruciate ligament replacement operations with free patellar tendon transplantation. Modification by surgical technique and surgery timing. Unfallchirurgie 21(5):240–246
68. Persson A, Fjeldsgaard K, Gjertsen JE, Kjellsen AB, Engebretsen L, Hole RM, Fevang JM (2014) Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004–2012. Am J Sports Med 42(2):285–291. doi:10.1177/0363546513511419
69. Persson A, Kjellsen AB, Fjeldsgaard K, Engebretsen L, Espehaug B, Fevang JM (2015) Registry data highlight increased revision rates for endobutton/biosure HA in ACL reconstruction with hamstring tendon autograft: a nationwide cohort study from the Norwegian knee ligament registry, 2004–2013. Am J Sports Med. doi:10.1177/0363546515584757
70. Pickle A, Campbell A, Johnson DH (2007) Anterior cruciate reconstruction. In: Johnson DH, Pedowitz RA (eds) Practical orthopaedic sports medicine and arthroscopy. Williams & Wilkins, Lippincott, pp 577–598
71. Plancher KD, Steadman JR, Briggs KK, Hutton KS (1998) Reconstruction of the anterior cruciate ligament in patients who are at least forty years old. A long-term follow-up and outcome study. J Bone Joint Surg Am 80(2):184–197
72. Portland GH, Martin D, Keene G, Menz T (2005) Injury to the infrapatellar branch of the saphenous nerve in anterior cruciate ligament reconstruction: comparison of horizontal versus vertical harvest site incisions. Arthroscopy 21(3):281–285. doi:10.1016/j.arthro.2004.10.018
73. Proctor CS, Jackson DW, Simon TM (1997) Characterization of the repair tissue after removal of the central one-third of the patellar ligament. An experimental study in a goat model. J Bone Joint Surg Am 79(7):997–1006
74. Purnell ML, Larson AI (2009) Mini-incision patellar tendon harvest and anterior cruciate ligament reconstruction using critical bony landmarks. Sports Med Arthrosc 17(4):234–241. doi:10.1097/JSA.0b013e3181c14760

75. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind M (2014) Comparison of hamstring tendon and patellar tendon grafts in anterior cruciate ligament reconstruction in a nationwide population-based cohort study: results from the danish registry of knee ligament reconstruction. Am J Sports Med 42(2):278–284. doi:10.1177/0363546513509220
76. Rodeo SA, Arnoczky SP, Torzilli PA, Hidaka C, Warren RF (1993) Tendon-healing in a bone tunnel. A biomechanical and histological study in the dog. J Bone Joint Surg Am 75(12):1795–1803
77. Sanchis-Alfonso V, Subias-Lopez A, Monteagudo-Castro C, Rosello-Sastre E (1999) Healing of the patellar tendon donor defect created after central-third patellar tendon autograft harvest. A long-term histological evaluation in the lamb model. Knee Surg Sports Traumatol Arthrosc 7(6):340–348
78. Shaffer B, Gow W, Tibone JE (1993) Graft-tunnel mismatch in endoscopic anterior cruciate ligament reconstruction: a new technique of intraarticular measurement and modified graft harvesting. Arthroscopy 9(6):633–646
79. Shaieb MD, Kan DM, Chang SK, Marumoto JM, Richardson AB (2002) A prospective randomized comparison of patellar tendon versus semitendinosus and gracilis tendon autografts for anterior cruciate ligament reconstruction. Am J Sports Med 30(2):214–220
80. Shelbourne KD, Klootwyk TE, Decarlo MS (1992) Update on accelerated rehabilitation after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 15(6):303–308. doi:10.2519/jospt.1992.15.6.303
81. Shelbourne KD, Nitz P (1992) Accelerated rehabilitation after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 15(6):256–264. doi:10.2519/jospt.1992.15.6.256
82. Shelbourne KD, Trumper RV (1997) Preventing anterior knee pain after anterior cruciate ligament reconstruction. Am J Sports Med 25(1):41–47
83. Soldado F, Reina F, Yuguero M, Rodriguez-Baeza A (2002) Clinical anatomy of the arterial supply of the human patellar ligament. Surg Radiol Anat 24(3–4):177–182. doi:10.1007/s00276-002-0042-5
84. Spindler KP, Kuhn JE, Freedman KB, Matthews CE, Dittus RS, Harrell FE Jr (2004) Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring: does it really matter? A systematic review. Am J Sports Med 32(8):1986–1995
85. Stein DA, Hunt SA, Rosen JE, Sherman OH (2002) The incidence and outcome of patella fractures after anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg 18(6):578–583. doi:10.1053/jars.2002.30658
86. Tanzer M, Lenczner E (1990) The relationship of intercondylar notch size and content to notchplasty requirement in anterior cruciate ligament surgery. Arthroscopy 6(2):89–93
87. Tifford CD, Spero L, Luke T, Plancher KD (2000) The relationship of the infrapatellar branches of the saphenous nerve to arthroscopy portals and incisions for anterior cruciate ligament surgery. An anatomic study. Am J Sports Med 28(4):562–567
88. Tomita F, Yasuda K, Mikami S, Sakai T, Yamazaki S, Tohyama H (2001) Comparisons of intraosseous graft healing between the doubled flexor tendon graft and the bone-patellar tendon-bone graft in anterior cruciate ligament reconstruction. Arthroscopy 17(5):461–476. doi:10.1053/jars.2001.24059
89. Tria AJ Jr, Alicea JA, Cody RP (1994) Patella baja in anterior cruciate ligament reconstruction of the knee. Clin Orthop Relat Res 299:229–234
90. van Grinsven S, van Cingel RE, Holla CJ, van Loon CJ (2010) Evidence-based rehabilitation following anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18(8):1128–1144. doi:10.1007/s00167-009-1027-2
91. Verma NN, Dennis MG, Carreira DS, Bojchuk J, Hayden JK, Bach BR Jr (2005) Preliminary clinical results of two techniques for addressing graft tunnel mismatch in endoscopic anterior cruciate ligament reconstruction. J Knee Surg 18(3):183–191
92. Weinstabl R, Wagner M, Schabus R, Firbas W (1986) Anatomical bases of patellar tendon grafts used in anterior cruciate ligament reconstruction. Surg Radiol Anat 8(3):163–167
93. Xie X, Liu X, Chen Z, Yu Y, Peng S, Li Q (2015) A meta-analysis of bone-patellar tendon-bone autograft versus four-strand hamstring tendon autograft for anterior cruciate ligament reconstruction. Knee 22(2):100–110. doi:10.1016/j.knee.2014.11.014
94. Yanke A, Ellman MB, Sherman SL, Bach BR Jr (2012) Graft-tunnel mismatch in bone-tendon-bone ACL reconstruction: prevention and treatment. Tech Orthop 27(2):153–157
95. Yunes M, Richmond JC, Engels EA, Pinczewski LA (2001) Patellar versus hamstring tendons in anterior cruciate ligament reconstruction: a meta-analysis. Arthroscopy 17(3):248–257
96. Zarins B (2007) Technique for harvesting a mid-third patella tendon graft for ACL reconstruction. In: Prodromos CC (ed) The anterior cruciate ligament: reconstruction and basic science. Elsevier, Philadelphia, pp 101–105

12

Technical Considerations for Quadriceps Tendon Harvest

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12.1 Background

Graft options for anterior cruciate ligament reconstruction (ACL) is one of the most commonly studied topics in orthopedic sports medicine, yet controversy remains with regard to which graft is best. Cost, cosmesis, ease of harvest, infection, donor site morbidity, clinical outcomes, rerupture rates, fixation, and surgeon familiarity all factor into a surgeon's decision when choosing a graft. Bone-tendon-bone (BTB) grafts are considered to be the "gold standard" to which other autografts are compared. Proponents of BTB grafts cite bone-to-bone healing, rigid fixation, lower rerupture rates, and intact hamstrings which act as a secondary stabilizer to anterior tibial translation. Proponents of hamstring autografts cite lower donor site morbidity, an intact extensor mechanism, lower rates of late osteoarthrosis, and avoidance of graft-tunnel mismatch [12]. Autologous quadriceps tendon (QT) graft for ACL reconstruction was originally described in 1979 by Marshall et al. [9]. Despite decades of success with this graft, QT remains infrequently used compared to alternative autografts [17], although interest in this graft seems to be increasing [10, 17, 18]. Nevertheless, QT is an incredibly versatile graft option which can be used in the primary or revision setting for single-bundle or double-bundle reconstructions, via a transtibial, anatomic, or all-inside techniques. The QT is unique in the sense that it allows the surgeon to harvest only "what is needed" and leave the remaining anatomy intact. Additionally, the tendon can be harvested with or without a patellar bone plug making it an excellent choice for epiphyseal sparing techniques in skeletally immature patients. Histologic and biomechanical properties of QT make it a favorable choice for ACL reconstruction [1, 6, 7, 11, 13]. Clinical outcome studies demonstrate similar outcomes to alternative autografts, with low donor site morbidity [4, 5, 8, 13]. Graft size can easily be

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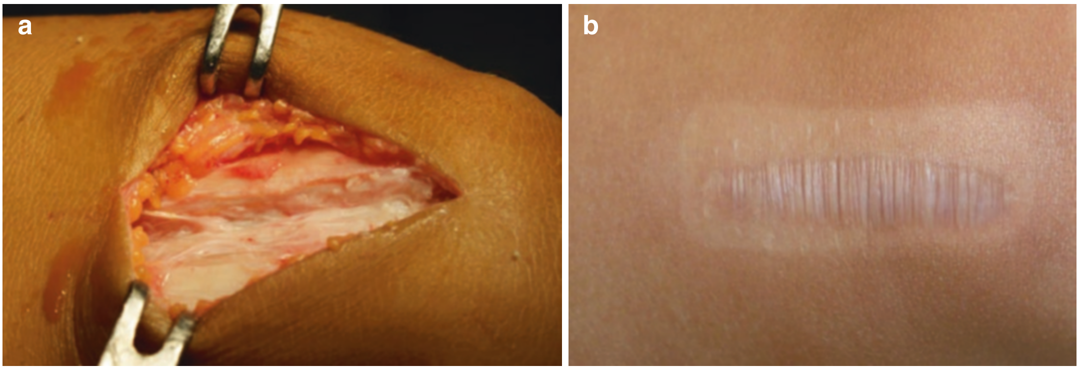


Fig. 12.1 (**a**) Incision and (**b**) scar following conventional quadriceps tendon harvest

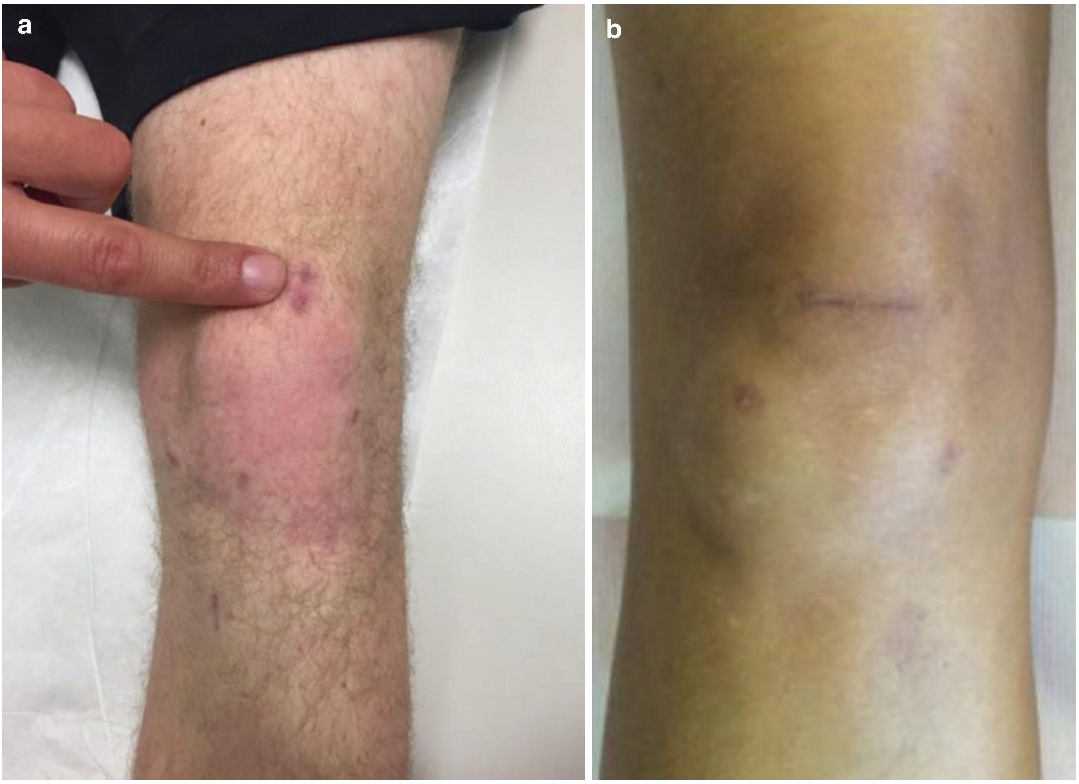


Fig. 12.2 Cosmetic appearance following minimally invasive quadriceps tendon harvest via (**a**) longitudinal or (**b**) horizontal incision

predicted from preoperative imaging studies [16, 20]. We think that the widespread use of QT has been limited by the historically cumbersome harvesting and less attractive cosmetic results compared to other autografts (Fig. 12.1).

The minimally invasive harvest techniques described in this chapter, in conjunction with recent development of specialized instrumentation, allow for a reproducible, safe, and easy graft harvest with improved cosmetic appearance (Fig. 12.2).

12.2 Indications and Contraindications

The QT is an appropriate choice for most patients undergoing ACL reconstruction. We have used QT as a primary graft option for several years in patients of all ages and activity levels, including elite athletes. Patients who perform a significant amount of kneeling for sport or employment and those with coexisting medial collateral ligament injury are excellent candidates for QT ACL reconstruction as the anterior knee pain associated with BTB harvest can be avoided and the dynamic stability provided by the medial hamstrings can be preserved. Graft-tunnel mismatch can be avoided in patients with longer patellar tendons. Contraindications for QT ACL reconstruction are few. These include prior quadriceps tendon surgery or injury, quadriceps tendinopathy, untreated coagulopathy, or large cavitary lesions in the revision setting.

12.3 Anatomy

The anatomy of the quadriceps tendon has traditionally been described as trilaminar, with the superficial fibers coming from the rectus femoris, the vastus medialis and vastus lateralis coalescing to form the middle layer, and the deepest portion extending from the vastus intermedius. In reality, this is a simplification of the great variation in contribution and pattern of fibers [19]. While the deeper fibers insert on the anterior edge of the superior pole of the patella, the most superficial fibers continue anterior to the patella and join the patellar tendon, and the most medial and lateral fibers contribute to the patellar retinaculum. The synovial tissue lines the deep surface of the quadriceps tendon as it forms the roof of the suprapatellar pouch extending approximately 5 cm above the superior pole of the patella [15].

The quadriceps tendon is thickest at the patellar insertion, on average 16 mm in female patients and 18 mm in male patients, and thins proximally as the contributing fibers separate from a common tendon at about 5–6 cm proximal to the insertion [20]. The average thickness of the central portion of this common tendon is 7–8 mm, and the average width is 27 mm [6, 20]. The average total length of the quadriceps tendon from the superior pole of the patella to the myotendinous junction of the rectus femoris is around 8 cm and correlates highly with patient height [20]. This allows for a graft of consistent length (7–8 cm), depth (6–7 mm), and width (9–10 mm) to be harvested [2] with an intra-articular volume 187.5 % greater than that of a similar-width patellar tendon graft taken from the same subject [20]. The vascular supply to the quadriceps tendon includes contributions from medial, lateral, and peripatellar arcades [21]. The lateral perforating vessels tend to be at greatest risk of being encountered during harvest.

12.4 Preoperative Planning

The quadriceps tendon autograft has less variability in diameter when compared to hamstring autograft, and its thickness can be evaluated preoperatively on most routinely ordered knee MRIs. The quadriceps tendon should be measured at the midsagittal point of maximal thickness, 3 cm proximal to the superior pole of the patella (Fig. 12.3). It is unusual for the quadriceps tendon thickness to be inadequate for ACL reconstruction, as the intra-articular volume of

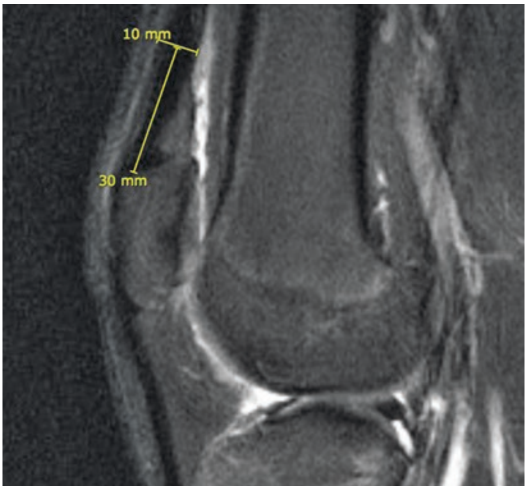


Fig. 12.3 Midsagittal measurement of quadriceps tendon thickness is performed 3 cm proximal to the proximal pole of the patella

graft tends to be larger and closer to anatomic than bone-tendon-bone reconstructions. Although partial-thickness grafts are preferred, a full-thickness graft should be planned if the tendon is less than 6 mm thick. We have not noticed any functional difference between patients who have received partial vs. full-thickness harvests if capsular rents are repaired.

12.5 Surgical Technique

12.5.1 Exposure of the QT

Examination of the injured knee is performed following induction of general anesthetic. A tourniquet is applied to the operative leg, which is then placed in a circumferential leg holder. The operative leg should rest at ninety degrees of knee flexion, putting tension on the extensor mechanism during graft harvest. The operative leg is then prepped and draped in a sterile fashion (Fig. 12.4).

Diagnostic arthroscopy can be performed before or after graft harvest according to surgeon preference. The distal vastus medialis obliquus and proximal pole of the patella are marked. A 1.5–2-cm mark is made at the planned incision site, starting just lateral to the midpoint of the superior pole of the patella, extending proximally along the length of the tendon longitudinally (Fig. 12.4). Alternatively, a 2–3-cm transverse incision over the superior boarder of the patella may be used. If arthroscopy is performed prior to graft harvest, it is important to suction all arthroscopy fluid from the knee, as capsular distention can make full-thickness violations more likely. Local anesthetic is injected into the planned incision site, which helps to distend the subcutaneous and areolar tissue. A 15-blade scalpel is used to

Fig. 12.4 Positioning with the operative leg in a circumferential leg holder and nonoperative leg in a lithotomy leg holder. The bony landmarks, arthroscopy portals, and harvest incision are marked

make the harvest incision, and the subcutaneous and areolar tissue is widely excised (Fig. 12.5). This step is critical for adequate visualization through the small incision. The paratenon is incised, and a RayTech sponge is used over a key elevator to sweep soft tissue off the anterior QT and anteriorly over the patella. An Army-Navy retractor or alternatively a long Langenbeck retractor is then placed. The arthroscope may be introduced into the wound with the fluid off, visualizing the tendon. The VMO, vastus lateralis, and distal rectus femoris musculotendinous junction are identified (Fig. 12.6). Crossing vessels should be coagulated with electrocautery or radiofrequency ablator to avoid postoperative hematoma at the harvest site. The arthroscope is advanced to the distal rectus femoris musculotendinous junction, and the arthroscope light source is used to transilluminate the skin over the anterior thigh. A mark is placed in the center of the point of maximum transillumination, which corresponds to the distal rectus femoris musculotendinous junction (Fig. 12.7). The distance from the proximal pole of the patella to the mark over the distal rectus femoris is measured. This distance represents the maximum length that is obtainable with an all soft tissue graft and usually measures over 8 cm.

Fig. 12.5 The subcutaneous tissue and areolar tissue are widely excised

Currently two different instrumentations for minimally invasive quadriceps tendon harvest are in clinical use:

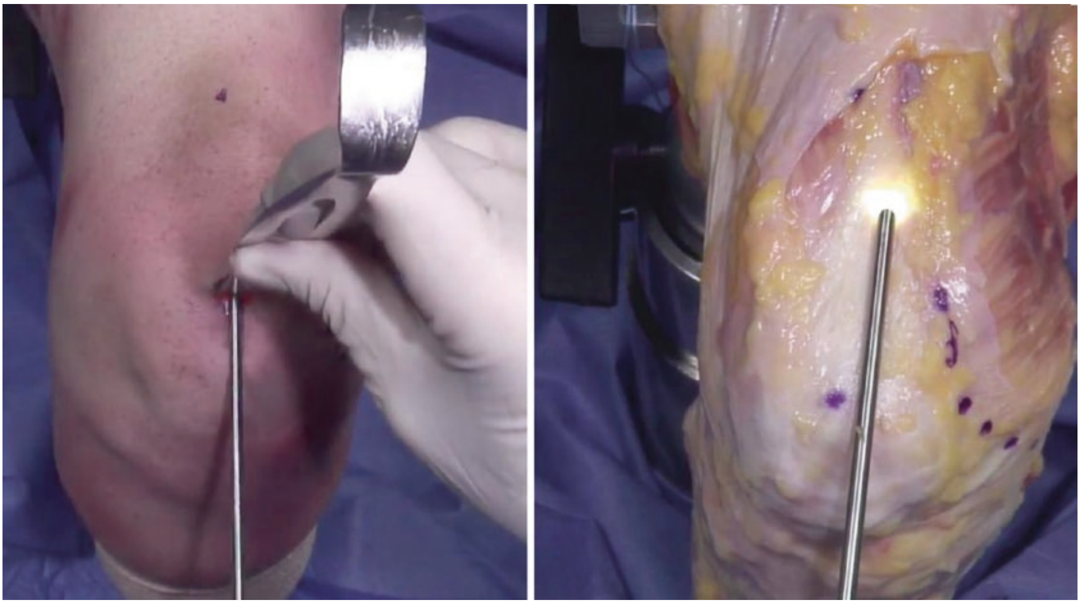


Fig. 12.6 The arthroscope (with fluid off) is used to view the quadriceps tendon, vastus medialis obliquus, vastus lateralis, and rectus femoris

12.5.2 Quad Tendon Harvesting System [Arthrex (Naples, FL)] [14]

With the knee at 90° of flexion, the Arthrex (Naples, FL) triple-blade harvest knife is used to incise the tendon starting just proximal to the superior pole of the patella, advancing toward the musculotendinous junction of the rectus femoris, which is identified by the mark previously placed on the anterior skin (Fig. 12.8). Markings on the knife handle allow for measurement of the QT incision. A 15 blade is used to extend the distal parallel incisions to the proximal pole of the patella, tapering the graft slightly, as graft diameter will increase slightly with later suture addition and graft preparation. The transverse limbs are connected, subperiosteally dissecting the tendon off of the patella. Proximal dissection is continued with metzenbaum scissors or scalpel. Tendon harvest depth is referenced off of the vertical limbs created by the triple-blade harvest knife. A layer of fat usually exists between the tendon and capsule. If fat is encountered, avoid deeper dissection or risk capsular violation if planning for a partial-thickness harvest. An Allis clamp can be placed on the distal tendon, which facilitates control and tension on graft as dissection is carried out proximally.

Fig. 12.7 The arthroscope is advanced to the level of the distal musculotendinous junction of the rectus femoris and light source turned to transilluminate the skin over the anterior thigh, and a mark is placed in the center of transillumination

Once 3 cm of tendon has been dissected free, an Arthrex Fiberloop (Naples, FL) suture is used to place 4 throws in the tendon, starting 1.5–2 cm proximal to the dissected tendon end, continuing distally, locking the last stitch, which exits the central portion of the tendon. The needle is left in place for later graft preparation. Tension is placed on these sutures during further proximal dissection, which is continued with metzenbaum scissors. Once 4–5 cm of tendon has been elevated, the Arthrex (Naples, FL) stripper/cutter is used to first strip and then cut the tendon, with firm tension on the previously placed sutures (Fig. 12.9). Currently, we harvest grafts 6.5–7 cm in length when performing anatomic

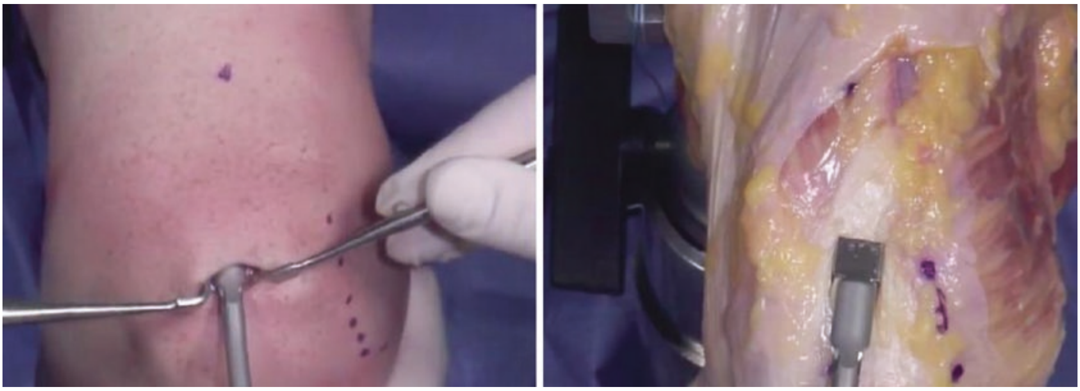


Fig. 12.8 The triple-blade harvest knife (Arthrex, Naples, FL) is used to incise the tendon longitudinally, starting proximal to the patella and advancing in the direction of the previously placed mark on the skin identifying the distal rectus femoris musculotendinous junction

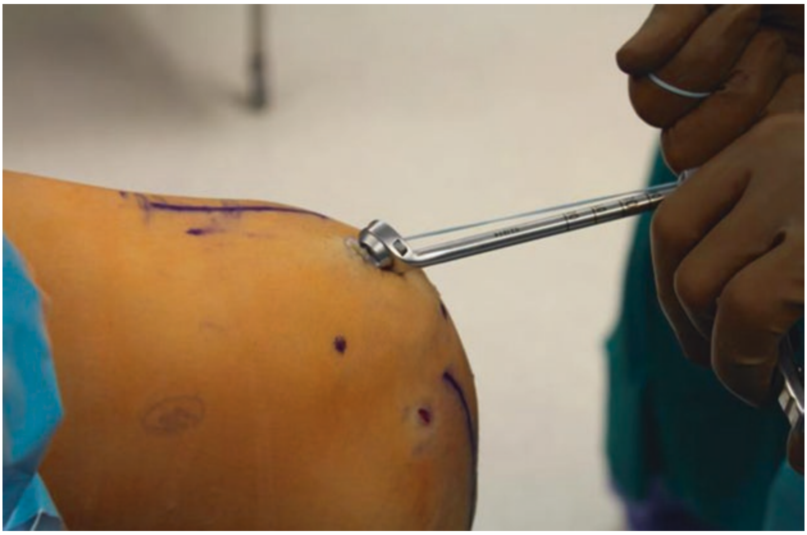


Fig. 12.9 The stripper/cutter device (Arthrex, Naples, FL) is used for proximal dissection and final transection of the graft proximally

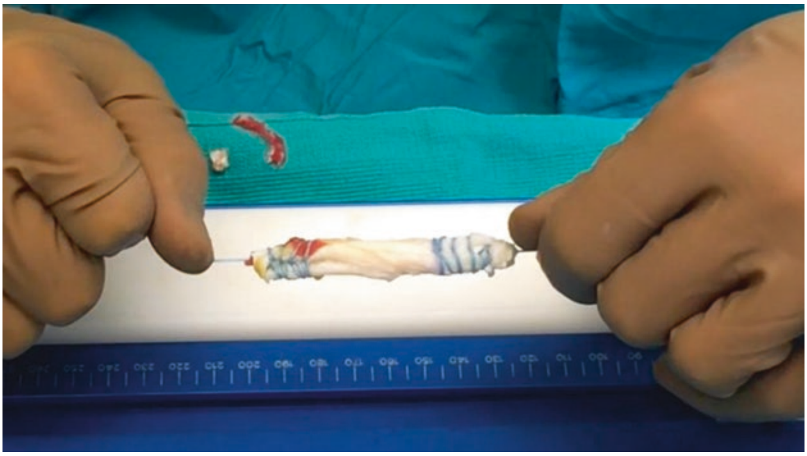


Fig. 12.10 The soft tissue quadriceps tendon graft is then prepared and sized

ACL reconstruction with an accessory medial portal technique and suspensory fixation. The harvested graft is delivered from the wound and brought to the back table for graft preparation and sizing (Fig. 12.10).

The arthroscope is then reinserted (fluid off) into the incision with an Army-Navy retractor at the proximal apex. The harvest site is inspected for full-thickness rents. Any capsular violation or areas of full-thickness harvest are closed with 2.0-Vicryl suture. If a partial-thickness harvest is confirmed, no deep closure is needed. A strip of gelfoam is placed in the harvest site, and the subcutaneous tissue and skin is closed.

Graft preparation The smaller end of the graft (usually the patellar side) is usually used on the femoral side for reconstruction. The needle left in places from earlier tendon whipstitch is placed through the loop of the Tightrope RT, and three or four whipstitches are then placed back in the tendon, starting 5 mm from the end, and proceeding toward the middle of the graft. The needle is then cut off, and suture limbs are wrapped around the graft and tied. The knot can be shuttled into the substance of the graft with a free needle. A second Fiberloop is used to whipstitch the multilaminar proximal of the graft in a similar fashion as

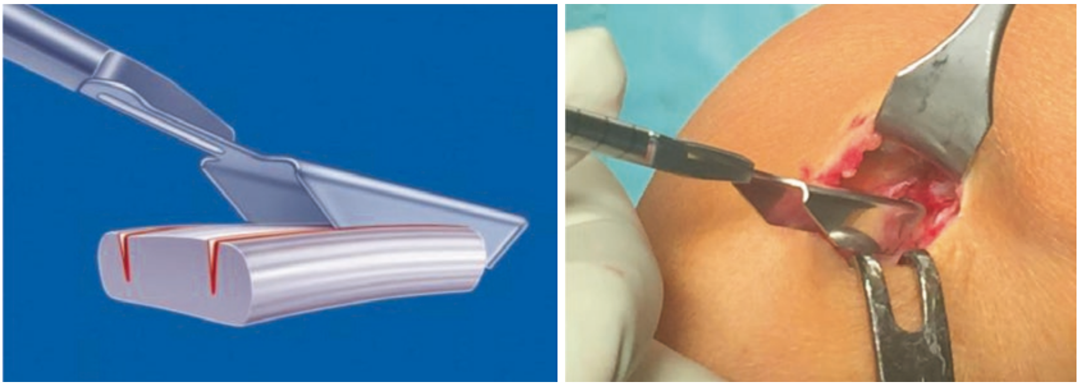


Fig. 12.11 The double knife (Karl Storz, Tuttlingen) is then introduced starting centrally on the superior patella boarder and pushed proximally

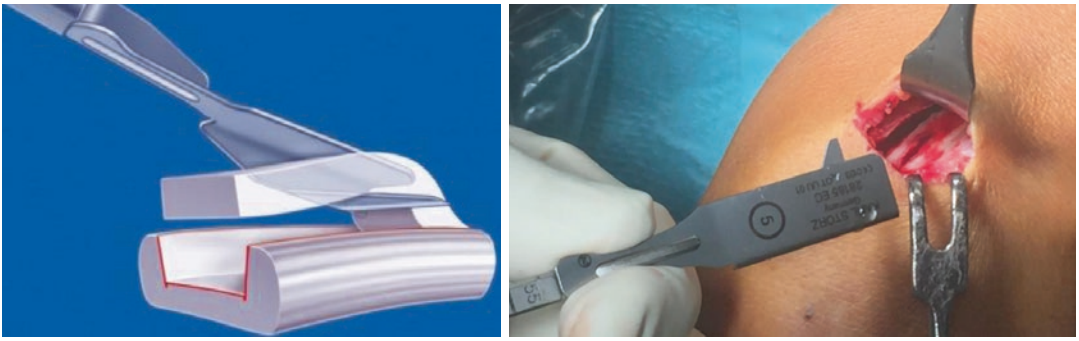


Fig. 12.12 The tendon separator of 5 mm (Karl Storz, Tuttlingen) is introduced and advanced proximally

previously used, with four throws placed, locking the last stitch before the suture exits the central portion of the graft.

12.5.3 QuadCut System [Karl Storz (Tuttlingen, Germany)] [3]

A double knife (Karl Storz, Tuttlingen) in 8–12-mm width is then introduced starting over the middle or slightly lateral to the middle of the superior patella boarder and pushed up to a minimum of 6 cm if used with a bone block or 7 cm if used as a soft tissue graft (Fig. 12.11). The thickness of the graft is then determined using a 5-mm tendon separator (Karl Storz, Tuttlingen). The separator is then pushed proximal to the same length mark (Fig. 12.12). Using a 5-mm tendon separator commonly leaves the recess closed and avoids fluid leakage during arthroscopy in most cases. A 5 × 10 mm graft approximates an 8-mm graft diameter of a round graft and a 5 × 12 mm graft approximates a 9-mm round graft. Finally, the tendon strip is cut subcutaneously using a special tendon cutter (Karl Storz, Tuttlingen) (Fig. 12.13), and the graft is retrieved through the skin incision.

QT *with* a bone block:

The tendon strip is elevated and then followed distally until its bony attachment. The dimensions of the bone block (1.5–2-cm length and respective graft width) are outlined. The bone cuts are made with an oscillating saw, starting with the longitudinal cuts. The graft is then elevated, and the final cut

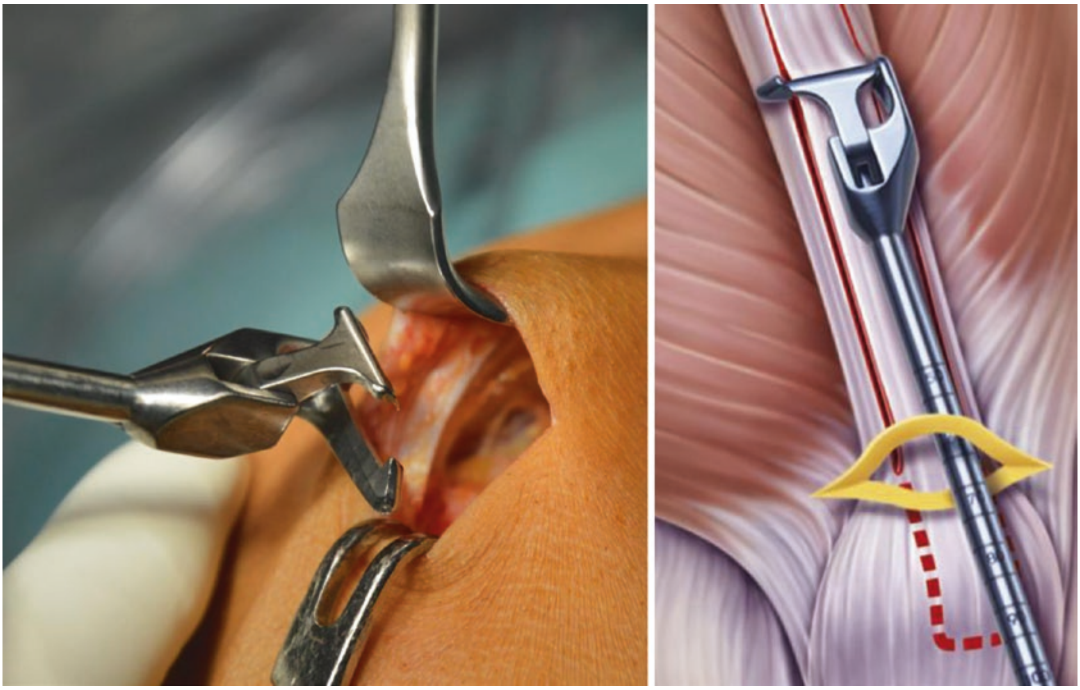


Fig. 12.13 The tendon strip is cut subcutaneously by a special tendon cutter (Karl Storz, Tuttlingen)

determining the thickness of the bone block is made from proximal to distal. The bone block is then easily elevated with a chisel (Fig. 12.14). To minimize the risk of patella fracture, forceful use of chisel and hammer to remove the block should be avoided. Finally, the tendon defect is closed, and the prepatellar bursal tissue layers are carefully closed over the bony defect.

Graft preparation The bone block is prepared to the appropriate diameter, and one or two 1.5-mm holes are drilled through. The bone block can then be mounted to a flip button (e.g., EndoButton® [Smith & Nephew], Flipptack® [Karl Storz, Tuttlingen]) by strong non-resorbable sutures (e.g., No. 2 FibreWire® [Arthrex, Naples, FL]) or a resorbable pull-out suture if the graft will be fixed with an interference screw on the femur. Two whipstitch sutures are placed in the distal end of the graft using non-resorbable No. 2 suture material (Fig. 12.15).

QT *without* a bone block:

The tendon strip is elevated and then followed distally until its bony attachment. The parallel longitudinal cuts are continued about 2 cm distally with a 15-blade scalpel. The QT graft is then subperiosteally elevated from the surface of the patella (Fig. 12.16) and detached. Finally, the tendon defect is closed.

Graft preparation The periosteal part of the graft is folded in the middle, and whipstitch sutures are placed on each side of the graft using a strong No. 2 suture (e.g., No. 2 FibreWire® [Arthrex, Naples, FL] (Fig. 12.17). This will result in a smooth round end of the graft, which allows easier graft passage. The sutures are then passed through a flip button (e.g., EndoButton® [Smith & Nephew], Flipptack® [Karl Storz, Tuttlingen]) for later fixation. Alternatively resorbable sutures may be used if a soft tissue interference screw is planned for femoral graft fixation. Two

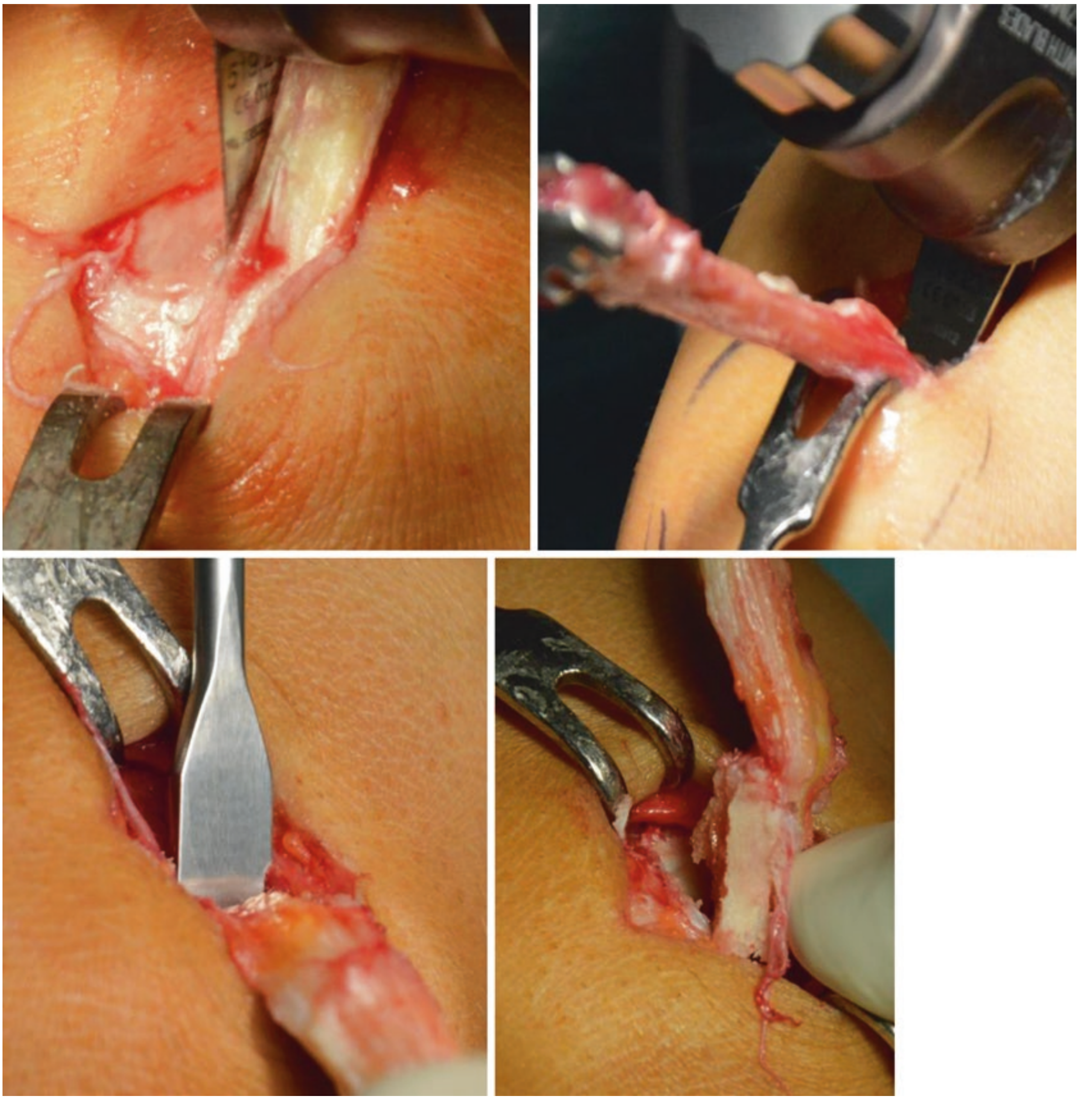
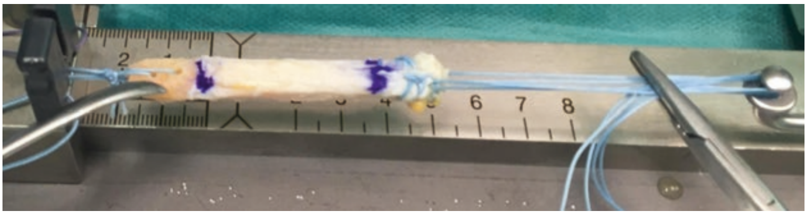


Fig. 12.14 The bone block is harvested using an oscillating saw

Fig. 12.15 The final QT graft with bone block mounted to a FlippTack (Karl Storz, Tuttlingen)



whipstitch sutures are placed in the distal end of the graft using non-resorbable No. 2 suture material (Fig. 12.18).

12.6 Rehabilitation

Rehabilitation following quadriceps tendon autograft ACL reconstruction is similar to other autograft techniques. It is important to maintain terminal extension with full early motion stretching and exercises. Weight bearing may begin when quadriceps function returns, and in-line jogging can be safely permitted at 3 months. As with any ACL reconstruction technique, functional testing is recommended prior to return to sports.

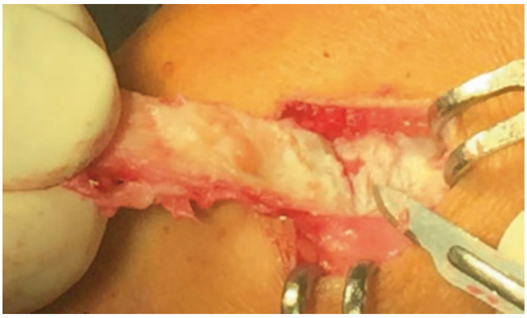


Fig. 12.16 The QT graft is pulled distally, and a 2-cm strip of periosteum in the appropriate width is elevated

12.7 Complications

There is limited data on complications of quadriceps tendon harvest in the literature, but the rate of complications appears to be similar to other autograft choices, with equivalent incidence of graft rerupture and arthrofibrosis [13]. In our experience with over 600 ACL reconstructions using minimal invasive quadriceps tendon harvest, an uncommon complication is the development of a harvest site hematoma. This may occur if the quadriceps muscle is violated to a significant degree during graft harvest, especially laterally where the perforating vessels exist, and cause extensive bleeding after release of the tourniquet. Alternatively, if a full-thickness harvest is performed, the extravasation of intra-articular bleeding through a rent in the synovium may form a similar hematoma anterior to the remaining quadriceps tendon. Patients with hematomas generally present with pain 2–3 days

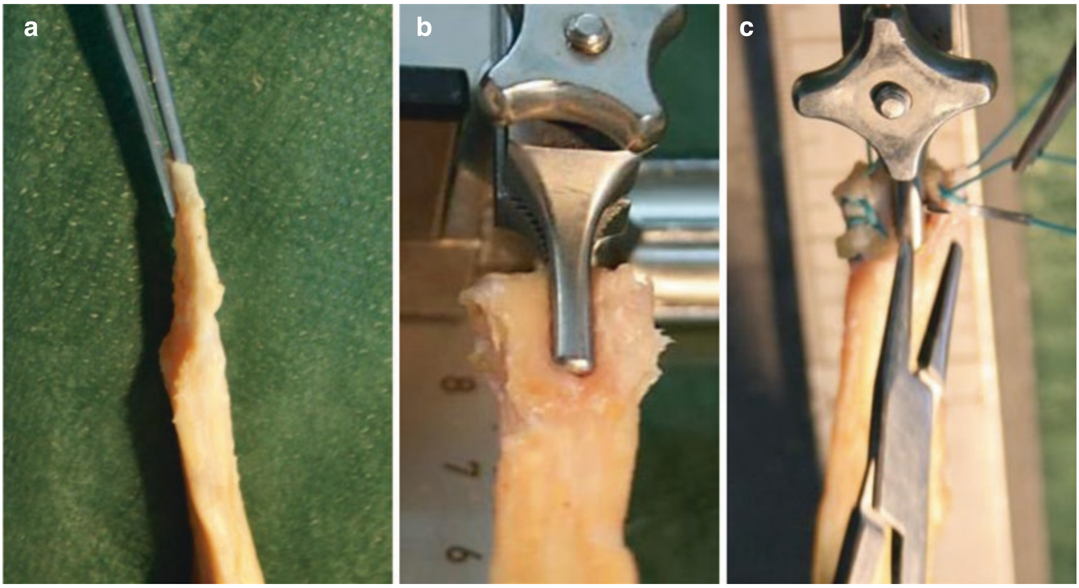


Fig. 12.17 (**a**) The periosteum is folded in the middle and (**b**) fixed in the clamp of a preparation board. (**c**) Whipstitch sutures are placed on each side of the graft using non-resorbable No. 2 suture material

Fig. 12.18 The final soft tissue QT graft mounted to a FlippTack (Karl Storz, Tuttlingen)

after surgery, swelling directly under the harvest site wound if seen. Once identified, it should be evacuated immediately and hemostasis assured. The risk of graft site hematoma formation can be reduced by centralizing the graft harvest within the quadriceps tendon, preferentially harvesting partial-thickness grafts, and terminating the proximal tendon harvest at or distal to the myotendinous junction of the rectus femoris (7–8 cm proximal to the tendon insertion on the patella). Another rare complication that has occurred is a retraction of the rectus femoris muscle after quadriceps tendon harvesting crossed the myotendinous junction. Despite the cosmetic deformity, there were no functional consequences.

12.8 Summary

While many knee surgeons have used the QT as a graft for ACL revision surgery, it has not yet achieved universal acceptance for primary ACL reconstruction. A main reason in our opinion is that conventional QT graft harvest has been technically demanding and has led to cosmetically less favorable results. However, with the development of new instrumentations and minimally invasive harvesting technique, the cosmetic outcome can be markedly improved and surgical time reduced. We think that with these improvements QT has become an attractive graft not only for revision but also for primary ACL reconstruction.

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References

1. Adams DJ, Mazzocca AD, Fulkerson JP (2006) Residual strength of the quadriceps versus patellar tendon after harvesting a central free tendon graft. Arthroscopy 22(1):76–79
2. DeAngelis JP, Fulkerson JP (2007) Quadriceps tendon – a reliable alternative for reconstruction of the anterior cruciate ligament. Clin Sports Med 26(4):587–596
3. Fink C, Herbort M, Abermann E, Hoser C (2014) Minimally invasive harvest of a quadriceps tendon graft with or without a bone block. Arthrosc Tech 3(4):e509–e513
4. Gorschewsky O, Klakow A, Pütz A, Mahn H, Neumann W (2007) Clinical comparison of the autologous quadriceps tendon (BQT) and the autologous patella tendon (BPTB) for the reconstruction of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 15(11):1284–1292
5. Han HS, Seong SC, Lee S, Lee MC (2008) Anterior cruciate ligament reconstruction: quadriceps versus patellar autograft. Clin Orthop Relat Res 466(1):198–204
6. Harris NL, Smith DA, Lamoreaux L, Purnell M (1997) Central quadriceps tendon for anterior cruciate ligament reconstruction. Part I: morphometric and biomechanical evaluation. Am J Sports Med 25(1): 23–28
7. Lee S (2007) Anterior cruciate ligament reconstruction with use of autologous quadriceps tendon graft. J Bone Joint Surg 89(suppl 3):116
8. Lund B, Nielsen T, Faunø P, Christiansen SE, Lind M (2014) Is quadriceps tendon a better graft choice than patellar tendon? A prospective randomized study. Arthroscopy 30:593–598
9. Marshall JL, Warren RF, Wickiewicz TL, Reider B (1979) The anterior cruciate ligament: a technique of repair and reconstruction. Clin Orthop Relat Res 143:97–106
10. Middleton KK, Hamilton T, Irrgang JJ, Karlsson J, Harner CD, Fu FH (2014) Anatomic anterior cruciate ligament (ACL) reconstruction: a global perspective. Part 1. Knee Surg Sports Traumatol Arthrosc 22(7):1467–1482
11. Sasaki N, Farraro KF, Kim KE, Woo SL-Y (2014) Biomechanical evaluation of the quadriceps tendon autograft for anterior cruciate ligament reconstruction: a cadaveric study. Am J Sports Med 42:723–730
12. Shelton WR, Fagan BC (2011) Autografts commonly used in anterior cruciate ligament reconstruction. J Am Acad Orthop Surg 19(5):259–264
13. Slone HS, Romine SE, Premkumar A, Xerogeanes JW (2015) Quadriceps tendon autograft for anterior cruciate ligament reconstruction: a comprehensive review of current literature and systematic review of clinical results. Arthroscopy 31(3):541–554
14. Slone HS, Xerogeanes JW (2014) Anterior cruciate ligament reconstruction with quadriceps tendon autograft. JBJS Essent Surg Tech 4(3):e16–e16

15. Stäubli HU (1997) The quadriceps tendon-patellar bone construct for ACL reconstruction. Sports Med Arthrosc Rev 5:59–67
16. Todd DC, Ghasem AD, Xerogeanes JW (2015) Height, weight, and Age predict quadriceps tendon length and thickness in skeletally immature patients. Am J Sports Med 43(4):945–952
17. van Eck CF, Illingworth KD, Fu FH (2010) Quadriceps tendon: the forgotten graft. Arthroscopy 26(4): 441–442
18. van Eck CF, Schreiber VM, Mejia HA et al (2010) “Anatomic” anterior cruciate ligament reconstruction: a systematic review of surgical techniques and reporting of surgical data. Arthroscopy 26(9):S2–S12
19. Waligora AC, Johanson NA, Hirsch BE (2009) Clinical anatomy of the quadriceps femoris and extensor apparatus of the knee. Clin Orthop Relat Res 467(12):3297–3306
20. Xerogeanes JW, Mitchell PM, Karasev PA, Kolesov IA, Romine SE (2013) Anatomic and morphological evaluation of the quadriceps tendon using 3-dimensional magnetic resonance imaging reconstruction: applications for anterior cruciate ligament autograft choice and procurement. Am J Sports Med 41(10):2392–2399
21. Yepes H, Tang M, Morris SF, Stanish WD (2008) Relationship between hypovascular zones and patterns of ruptures of the quadriceps tendon. J Bone Joint Surg Am 90(10):2135–2141

13

Acute ACL Rupture: A Biological Approach Through Primary ACL Repair and Augmentation with Bone Marrow Stimulation and Growth Factor Injection

Alberto Gobbi, Graeme P. Whyte,
and Georgios Karnatzikos

13.1 Introduction

Anterior cruciate ligament (ACL) injuries are common in recreational and competitive sporting activities. According to an ongoing study in the United States, an estimated 200,000 ACL reconstructions (ACLR) are performed annually, and the incidence of ACL injury is roughly one in 3,000 per year [1, 2]. The treatment of ACL injury is an area of considerable controversy, despite advances in sports medicine literature. The current gold standard for the treatment of acute ACL lesions is reconstruction with tendon graft, with reported success rates of 80 % [3–7]. Despite these successful outcomes, donor site morbidity, poor proprioception, and incomplete return to high-risk sports are potential disadvantages of this procedure [8–11]. In addition, there is the risk of iatrogenic injury and subsequent growth disturbance in skeletally immature patients due to distal femoral or proximal tibial growth plate violation [12, 13].

Considering the significant functional limitation that is often experienced by young, active patients who suffer from ACL injury, therapeutic options that restore function and allow return to sport in a timely manner should continue to be investigated in cases of acute partial ACL lesions [12–22]. Furthermore, developing a regenerative method for ACL repair would preserve the proprioceptive function and the architecture of the native ligament insertion, potentially optimizing biomechanical function [23, 24].

13.1.1 Is ACL Repair Feasible?

Numerous studies, using animal and in vitro models, have investigated ACL biology and the healing response to injury [25–30]. Rapid degeneration of the ACL has been observed following acute rupture, which is associated with a significant increase in collagenase activity and a decrease in total collagen content of the injured ligament [25]. The poor healing capabilities of the ACL, when compared to the medial collateral ligament (MCL), are well known [28]. The outgrowth of cells from ACL explants in vitro has been shown to be slower than from MCL explants, suggesting a lower proliferation and migration potential of ACL cells in comparison to those cells of MCL origin [27, 28]. In a rabbit model, a

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higher level of procollagen mRNA was consistently detected in normal MCL compared to that of normal ACL, suggesting higher collagen synthetic activity in the MCL and possible differences in their healing capacities [26].

Comparing the healing response of the ACL with other ligaments, the process of platelet-fibrin clot formation of injured ACL is typically poor [31]. Without this clot, the wound remains opened and this interferes with tissue remodeling and cellular migration, ultimately leading to non-healing of ruptured ligament. Circulating plasmin within the joint space may prematurely break down the fibrin clot, and this has been postulated to be a reason for inhibition of clot formation [32]. Moreover, synovial fluid has been shown to inhibit ACL fibroblast proliferation and migration [33], thereby retarding the healing of tissue. Developing strategies that could assist in the formation of a scaffold between the tendon ends to address this problem has become an area of active research and investigation.

13.1.2 Primary ACL Repair: Healing Stimulation

Primary suture repair of the torn portions of the ACL was previously popularized in the 1950s [15, 17]. Long-term follow-up studies demonstrated that these techniques led to failure rates up to 90 % and were therefore abandoned [16, 18, 19]. Despite these reports, recent investigations showed the possibility of ACL healing after primary suture of the ligament augmented with the use of growth factors and bone marrow-derived mesenchymal stem cells (MSCs) [20–22, 34–36]. The potential advantages over ACLR technique are the preservation of the ACL anatomy, kinematics, and proprioception, while donor site morbidity and postoperative muscular weakness are significantly reduced.

13.1.3 Cellular Therapies: Mesenchymal Stem Cells

The idea of "biological solutions for biological problems" has led to the development of less invasive procedures that have the potential to reduce morbidity while enhancing healing and functional recovery [34, 37]. Cellular therapies offer an interesting option in the treatment of ACL injury by addressing the deficiencies in healing response at a molecular level, leading to a more preferential biological cascade of healing processes. Steadman's "healing response therapy" was one of the earliest treatments described which extolled the role of MSCs in aiding the healing of a ruptured ACL in humans. The results of this therapy were reported as encouraging and are based on the multipotent nature of MSCs [20, 21].

MSCs were initially isolated from the bone marrow and since then have been reported to be isolated from a number of other tissues such as fat, muscle, skin, connective tissue, skin, and bone. The multilineage differentiation, ease of availability, and self-renewal capacity of MSCs have drawn the attention of researchers for obvious reasons [38, 39]. The phenotypic plasticity of these cells has generated a considerable enthusiasm to use them in repairing or regenerating connective tissue with ex vivo, tissue engineering, or in situ techniques. Given the similarity between ACL outgrowth cells and MSCs [40], there is potential for these cells to enhance the healing of a repaired ACL.

13.1.4 Platelet-Rich Plasma and Growth Factors

Bioactive proteins and growth factors play an important role in tissue healing as they can regulate key processes in tissue repair, including cell proliferation, chemotaxis, migration, cellular differentiation, and extracellular matrix synthesis. Platelet-rich plasma (PRP) contains many important growth factors that have been proven to enhance cellular proliferation and migration, as well as increase collagen production in in vitro studies [41, 42]. The rationale for the use of PRP is to stimulate the natural healing cascade and tissue regeneration by a "supraphysiologic" release of platelet-derived factors directly at the site of treatment. Autologous PRP can be obtained from simple blood extraction with a commercially available kit, although there is variability in PRP preparation methods and constituency of growth factors [57]. After the blood is collected into a tube containing anticoagulant, it undergoes a centrifugation process to produce PRP. Among the contained growth factors, platelet-derived growth factor (PDGF), fibroblast growth factor (FGF), bone morphogenetic protein (BMP), and transforming growth factor beta (TGF-β) have shown to enhance the healing of ligaments.

Kobayashi et al. [43] noted improved healing and vascularity following instillation of FGF in the canine ACL. Aspenberg et al. [44] reported an improved healing response in Achilles tendon with the use of growth differentiation factor 5 (GDF 5). These growth factors can be used along with synthetic scaffolds to enhance the process of ACL repair. Chen et al. [45] described the use of BMP 2 along with hydrogel and periosteum to stimulate tendon-bone healing in an ACL reconstruction model, showing that polyenylphosphatidylcholine (PPC)-BMP-hydrogel composite is an effective inducer of healing and can act as a matrix for encapsulation of cell and growth factors. The use of collagen-platelet composites has also been shown to have beneficial effects [41]. There is, however, disagreement in the literature, as Murray et al. [46] contested the role of PRP in ACL healing following their results in skeletally immature animals in which they performed ACL repair with or without PRP injection. The addition of PRP to the suture repairs did not improve anterior-posterior (AP) knee laxity, maximum tensile load, or linear stiffness of the ACL repairs after 14 weeks in vivo.

13.2 Study Group

Gobbi et al. [47], in a prospective case series, demonstrated that ACL primary repair combined with bone marrow stimulation and growth factor injection is an effective technique to restore knee stability and function in young athletes with acute partial ACL tears, at 5-year follow-up. Fifty patients (mean age 28.3 years) presenting with an acute partial acute ACL tear were treated by primary repair, bone marrow stimulation, and growth factor injection into the ligament.

The distribution of patients identified as having each type of ACL injury were:

- *Type I*: partial lesion (<100 %) of the anteromedial bundle (AM) in 30 patients
- *Type II*: partial lesion (<100 %) of the posterolateral bundle (PL) in eight patients
- *Type III*: both bundles partially torn (<100 %) in 12 patients
- *Type IV*: complete ACL tear (no patient)

Exclusion criteria: lesions not amenable to primary repair, mid-substance ACL tears, associated chondral lesions > grade 3 (ICRS classification), partial or complete tear of the lateral collateral ligament or posterior cruciate ligament, grade III MCL injury, patients with contralateral ligament knee injury, severe lower limb malalignment, and history of previous surgery on the same knee.

13.2.1 Surgical Technique

The patient is positioned supine under spinal anesthesia. The typical preparation and draping used for arthroscopically assisted ACL reconstruction are used. A routine arthroscopic evaluation of the knee by standard anteromedial and anterolateral portals is performed, and partial tearing of the ACL is confirmed (Fig. 13.1). Associated pathologies of other intra-articular structures are addressed prior to ACL repair. ACL repair is performed by passing No. 1 polydioxanone sutures (PDS) (Ethicon, Piscataway, New Jersey), using a Clever Hook or other suture-passing device, and the torn portions of ACL are secured together using a Duncan loop (Fig. 13.2). Using a 45° microfracture awl, several holes (1.5 mm in diameter, 3–4 mm apart, and 3 mm deep) are made around the anatomic femoral insertion of the ACL (Fig. 13.3a). PRP glue is prepared using a commercially available system (Arthrex Angel System, Naples, FL, US). Approximately 3 mL of PRP is isolated and activated with batroxobin enzyme (Plateltex ® act-S.R.O., Bratislava, SK) to produce

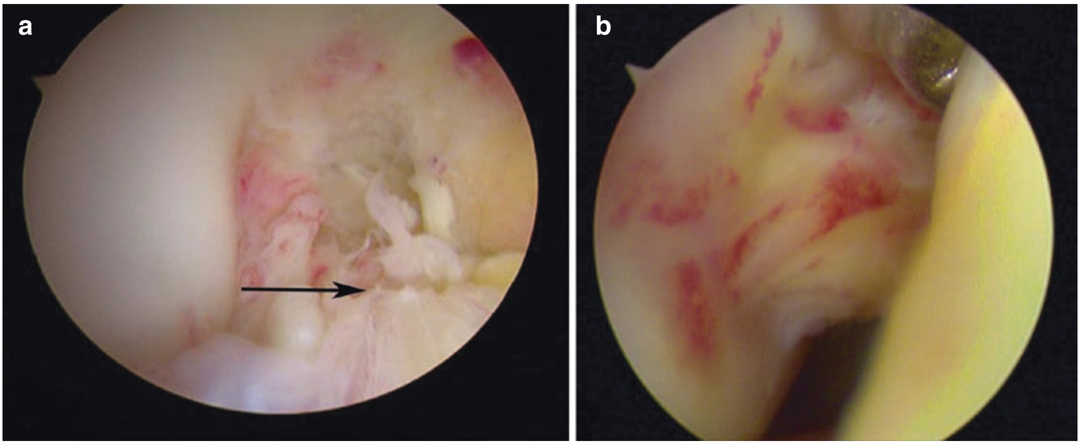

Fig. 13.1 (**a**) Subtotal rupture of the anteromedial ACL bundle, disrupted fibers continuous with distal insertion (*black arrow*). (**b**) Ecchymosis of the posterolateral ACL bundle

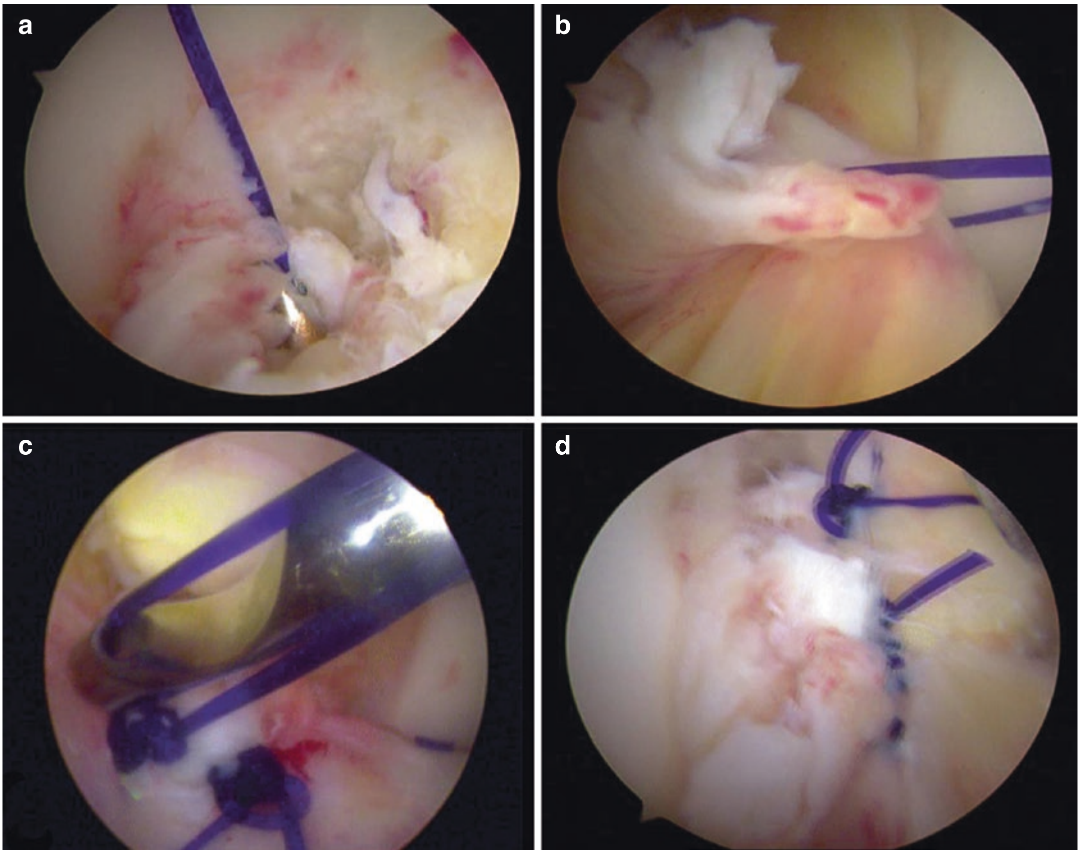

Fig. 13.2 Arthroscopic repair of the ACL demonstrating passage of No. 1 PDS suture from distal to proximal (**a**), suture apposition of distal and proximal torn fibers (**b**), tensioning of fibers and securing with knot fixation (**c**), and complete reapproximation of disrupted ACL fibers with three interrupted PDS sutures (**d**)

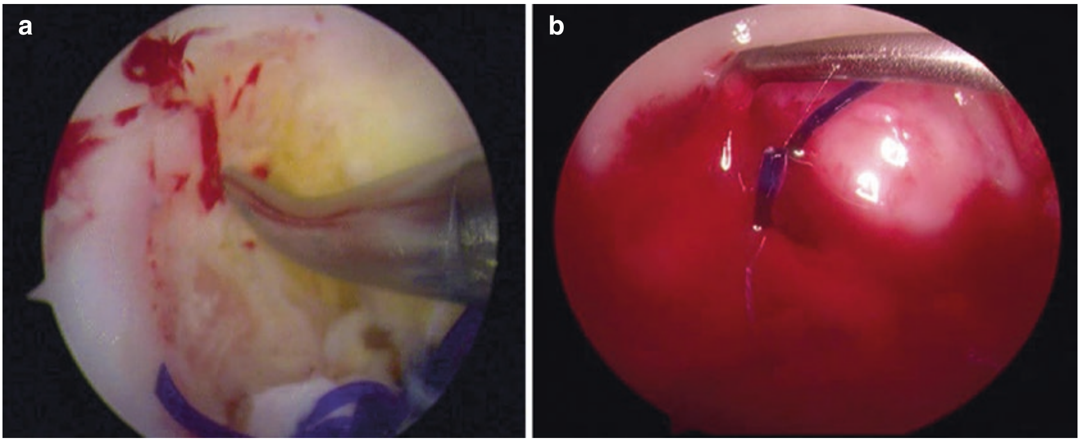

Fig. 13.3 Microfracture awl used to release marrow elements adjacent to ACL insertion within femoral notch (**a**) and application of activated bone marrow aspirate concentrate to repaired ligament (**b**)

a sticky PRP gel, which is injected at the repaired site to biologically augment the healing process (Fig. 13.3b). More recently, our preferred technique is to augment all ACL repairs with activated bone marrow aspirate concentrate in order to provide the healing ligament with MSCs as well as growth factors. Batroxobin or autologous thrombin may be used to activate the bone marrow aspirate concentrate, although the use of autologous thrombin requires an additional 15 min of centrifugation time.

13.2.2 Rehabilitation Protocol

All patients followed the same rehabilitation protocol [48]. The knee was kept in a brace locked in extension for 3 weeks, and patients were allowed partial weight bearing with crutches, followed by weight bearing as tolerated. A continuous passive motion machine was used for 4–6 h per day in a range between 20° and 60°, starting on the first postoperative day. The range of motion (ROM) was increased up to 90° by 2 weeks postoperatively and then gradually increased up to 120° of flexion thereafter. Full active ROM was achieved between 6 and 12 weeks after surgery. Running was allowed at 3 months. No contact sports were allowed before 5 months.

13.3 Results

All patients were available at final 5-year follow-up. No infections or major postoperative complications were seen in this case series. Four patients (8 %) had a re-tear during sporting activity and underwent ACLR within 2 years from primary ACL repair; for these patients, the most recent evaluation score completed at 1-year follow-up, prior to revision surgery, was included in the final analysis.

The difference in anterior translation of the knee compared to the unaffected side was reduced from 4.1 mm preoperatively to 1.4 mm at 5-year follow-up ($p<0.05$). A significant improvement in Tegner, single assessment numeric evaluation (SANE), Marx, Noyes, and Lysholm scores was observed at 5-year follow-up ($p<0.05$). The final International Knee Documentation Committee (IKDC) objective score was rated as normal in 39 patients (78 %), nearly normal in 10 patients, and abnormal in 1 patient. The 11 patients with a nearly normal or abnormal IKDC score had associated pathologies (meniscal or chondral lesions). Thirty-nine patients (78 %) fully resumed sporting activity. Return to sport was reached at a mean of 6 months postoperatively. Eleven patients (22 %) did not return to sport at pre-injury levels; in four of these patients, this was a personal choice unrelated to functional ability.

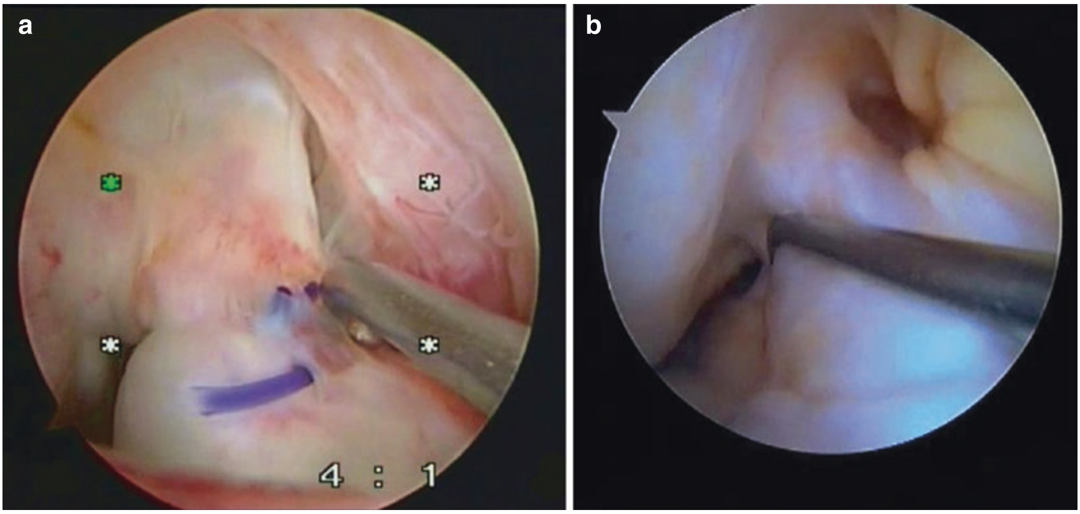

Fig. 13.4 Second-look arthroscopy performed at 4 weeks (**a**) and 6 months (**b**) after ACL repair with bone marrow stimulation and growth factor augmentation of partial ACL rupture. Confirmation of stability by arthroscopic probing demonstrated

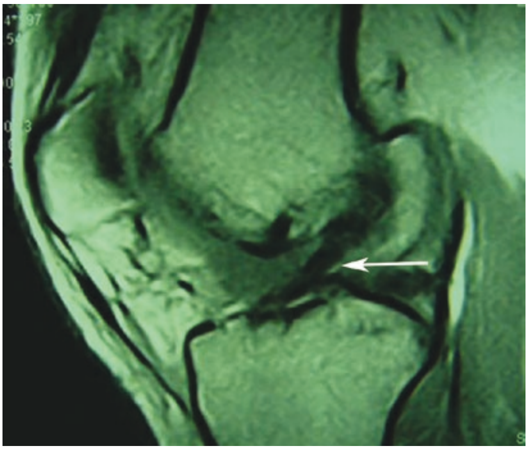

Fig. 13.5 Postoperative MRI of ACL (*white arrow*) at 8 months after ACL repair with bone marrow stimulation and growth factor augmentation of partial ACL rupture

Second-look arthroscopy was performed in six patients (12 %) and consistently revealed a healed ACL which was stable on probing and had minimal fibrous tissue contained within the healed ligament (Figs. 13.4 and 13.5).

13.4 Discussion

ACL primary repair combined with bone marrow stimulation and growth factor application is an effective technique to restore knee stability and function in young athletes presenting with partial ACL tears [47]. Potential benefits include preservation of the native ACL and avoidance of complications associated with ACLR surgery, such as loss of proprioception. MSCs and PRP have the capacity to act as a source of precursor cells and growth factors that have been shown to enhance ligamentous healing [43, 44]. Anatomic repair and apposition of the torn ligament fibers are essential, as gapping between ligament fascicles may prevent cell migration and tissue regeneration [31].

The potential benefits of MSCs in ACL repair have also been described by Steadman et al., who reported excellent outcomes in terms of knee stability, function, and return to sport [20, 49]. The authors investigated the results of this procedure in the treatment of proximal ACL tears in a group of 48 active individuals over 40 years of age and reported improved clinical outcomes after a minimum of 2-year follow-up. In another study, excellent clinical outcomes were reported in 10 of 13 athletically active, skeletally immature patients with proximal ACL tears treated with a "healing response" procedure (ACL femoral footprint microfracture) [21]. Interestingly, this procedure was performed without concomitant suture of the ACL.

In the present study group, 98 % of patients presented at final follow-up with a normal or near normal IKDC objective score and a Tegner score comparable to pre-injury levels. Improvement in other instruments (Marx, Noyes) indicated good outcomes and recovery of stability and function similar to pre-injury assessments. Although there are previous studies that have reported high re-rupture rates of the ACL (approximately 50 %) following primary repair [16, 19], the re-rupture rate of the present study cohort was significantly lower (8 %) and is comparable to the results following ACL reconstruction at similar time points [50, 51]. It should be highlighted, however, that not all ACL lesions can be treated with this technique; patient selection is essential and strict inclusion criteria should be followed. The relatively low proportion of partial ACL ruptures identified in young athletic individuals, combined with the requirement for adherence to a strict rehabilitation protocol, leads to a low number of available patients. The precise selection criteria, patient adherence to the physiotherapy regimen, and regular follow-up may be contributing factors to the high success rates (90 %) demonstrated at midterm follow-up.

Undoubtedly, biologic augmentation techniques to assist tissue repair and regeneration will continue to improve. For example, the addition of PRP preparations to MSCs has been shown to assist with the formation of bioactive composites suitable for the healing of tissue defects in vivo, by acting as a source of both growth factors and “working cells” [53]. The application of multiple biologics that have the potential to act synergistically may play an important role in the progress of regenerative medicine. Furthermore, with greater advances in tissue engineering and molecular biology, the development of scaffold and cell-scaffold composite technology may offer interesting therapeutic options to augment ligamentous repair. There has been reported acceleration of ligament healing by enhancement of ACL cell viability, metabolic activity, and collagen synthesis following the use of PRP-scaffold composites in experimental ACL models [42]. The underlying premise is that while PRP/MSCs will act as the source of growth factors and precursor cells, the scaffold acts both as a matrix in the cellular process and as a biomechanical support following primary repair of the ACL. This would provide a secure environment for the regenerative cells, separating them from the effects of circulating plasmin within the joint space, which is known to inhibit the process of fibrin clot formation.

The natural history of partial ACL ruptures should be considered when undertaking surgical management of such injury. In the active patient who wishes to return to sport, there may be progressive laxity and increasing functional limitation associated with partial ACL injury [52], and surgical treatment may be preferable early in the course of management. Although selective reconstruction of the AM bundle in cases of partial ACL rupture has been shown to restore stability [54, 55], standard ACL single-bundle reconstruction has not been compared to selective AM bundle reconstruction to a great extent in the literature [56]. The technique of ACL repair with biologic augmentation that has been described in our cohort of patients who had suffered partial ACL injury has demonstrated comparable outcomes to those expected in cases of either selective AM bundle reconstruction or a standard single-bundle technique. There is need for further controlled comparative studies to examine outcomes between surgical management techniques in patients with partial ACL injury in order to develop appropriate treatment guidelines.

Conclusion

ACL primary repair with bone marrow stimulation and growth factor application represents an effective procedure in the treatment of acute partial ACL tear. Patient selection is important, and strict inclusion criteria should be followed. Proper surgical technique and appropriate rehabilitation protocols are crucial. This treatment does not alter bony anatomy, so conversion to standard ACL reconstruction may be performed without difficulty in the event of failure. Further research should focus on defining the specific role of this technique in the treatment of acute partial ACL tears of the knee, and improvements in the understanding of cellular biology in ligamentous healing are necessary to optimize long-term patient outcomes.

References

1. Amiel D, Ishizue KK, Harwood FL, Kitabayashi L, Akeson WH (1989) Injury of the anterior cruciate ligament: the role of collagenase in ligament degeneration. J Orthop Res 7(4):486–493
2. Amiel D, Nagineni CN, Choi SH, Lee J (1995) Intrinsic properties of ACL and MCL cells and their responses to growth factors. Med Sci Sports Exerc 27(6):844–851
3. Andrish J, Holmes R (1979) Effects of synovial fluid on fibroblasts in tissue culture. Clin Orthop Relat Res 138:279–283
4. Aspenberg P, Forslund C (1999) Enhanced tendon healing with GDF 5 and 6. Acta Orthop Scand 70(1):51–54
5. Cabaud HE, Rodkey WG, Feagin JA (1979) Experimental studies of acute anterior cruciate ligament injury and repair. Am J Sports Med 7(1):18–22
6. Chen CH (2009) Strategies to enhance tendon graft – bone healing in anterior cruciate ligament reconstruction. Chang Gung Med J 32(5):483–493, Review
7. Cheng M, Wang H, Yoshida R, Murray MM (2010) Platelets and plasma proteins are both required to stimulate collagen gene expression by anterior cruciate ligament cells in three-dimensional culture. Tissue Eng A 16(5):1479–1489
8. Chouteau J, Testa R, Viste, Moven B (2012) Knee rotational laxity and proprioceptive function 2 years after partial ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 20(4):762–766
9. Feagin JA Jr, Curl WW (1976) Isolated tear of the anterior cruciate ligament: 5-year follow-up study. Am J Sports Med 4(3):95–100
10. Gobbi A, Bathan L, Boldrini L (2009) Primary repair combined with bone marrow stimulation in acute anterior cruciate ligament lesions: results in a group of athletes. Am J Sports Med 37:571–578
11. Gobbi A, Boldrini L, Karnatzikos G, Mahajan V (2012) Clinical outcomes and rehabilitation program after ACL primary repair and bone marrow stimulation. In: Doral MN (ed) Sports Injuries-prevention, diagnosis, treatment and rehabilitation. Springer, Berlin, pp 475–484
12. Gobbi A, Domzalski M, Pascual J, Zanazzo M (2005) Hamstring anterior cruciate ligament reconstruction: is it necessary to sacrifice the gracilis? Arthroscopy 21(3):275–280
13. Gobbi A, Francisco R (2006) Factors affecting return to sports after anterior cruciate ligament reconstruction with patellar tendon and hamstring graft: a prospective clinical investigation. Knee Surg Sports Traumatol Arthosc 14(10):1021–1028
14. Gobbi A, Karnatzikos G, Nakamura N, Mahajan V (2012) Next generation cartilage solutions. In: Doral MN (ed) Sports injuries: prevention, diagnosis, treatment and rehabilitation. Springer, Berlin, pp 739–749
15. Gobbi A, Karnatzikos G, Sankineani SR, Petrera M (2013) Biological augmentation of ACL re-fixation in partial lesions in a group of athletes: results at 5-year follow-up. Tech Orthop 28(2):180–184
16. Gobbi A, Karnatzikos G, Scotti C, Mahajan V, Mazzucco L, Grigolo B (2011) One-step cartilage repair with bone marrow aspirate concentrated cells and collagen matrix in full-thickness knee cartilage lesions: results at 2-year follow-up. Cartilage 2(3):286–299
17. Gobbi A, Karnatzikos G, Sankineani SR (2014) One-step surgery with multipotent stem cells for the treatment of large full-thickness chondral defects of the knee. Am J Sports Med 42(3):648–657
18. Gobbi A, Mahajan V, Karnatzikos G, Nakamura N (2012) Single- versus double-bundle ACL reconstruction: is there any difference in stability and function at 3-year follow-up? Clin Orthop Relat Res 470(3): 824–834
19. Hospodar SJ, Miller MD (2009) Controversies in ACL reconstruction: bone-patellar tendon-bone anterior cruciate ligament reconstruction remains the gold standard. Sports Med Arthrosc 17(4):242–246
20. Kaplan N, Wickiewicz TL, Warren RF (1990) Primary surgical treatment of anterior cruciate ligament ruptures. A long-term follow-up study. Am J Sports Med 18(4):354–358
21. Kiapour AM, Murray MM (2014) Basic science of anterior cruciate ligament injury and repair. Bone Joint Res 3(2):20–31
22. Kim S, Bosque J, Meehan JP, Jamali A, Marder R (2011) Increase in outpatient knee arthroscopy in the United States: a comparison of National Surveys of Ambulatory Surgery, 1996 and 2006. J Bone Joint Surg Am 93(11):994–1000
23. Kobayashi D, Kurosaka M, Yoshiya S, Mizuno K (1997) Effect of basic fibroblast growth factor on the healing of defects in the canine anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 5(3):189–194
24. Kocher MS, Saxon HS, Hovis WD, Hawkins RJ (2002) Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and the ACL Study Group. J Pediatr Orthop 22:452–457
25. Lohmander LS, Englund PM, Dahl LL, Roos EM (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769
26. Mall NA, Paletta GA (2013) Pediatric ACL injuries: evaluation and management. Curr Rev Musculoskelet Med 6(2):132–140
27. Murray MM, Fleming BC (2013) Biology of anterior cruciate ligament injury and repair: Kappa delta ann doner vaughn award paper 2013. J Orthop Res 31(10):1501–1506
28. Murray MM, Martin SD, Martin TL, Spector M (2000) Histological changes in the human anterior cruciate ligament after rupture. J Bone Joint Surg Am 82:1387–1397
29. Murray MM, Palmer M, Abreu E, Spindler KP, Zurakowski D, Fleming BC (2009) Platelet-rich plasma alone is not sufficient to enhance suture repair

of the ACL in skeletally immature animals: an in vivo study. J Orthop Res 27(5):639–645

30. Murray MM, Spindler KP, Abreu E, Muller JA, Nedder A, Kelly M, Frino J, Zurakowski D, Valenza M, Snyder BD, Conolly SA (2007) Collagen-platelet rich plasma hydrogel enhances primary repair of the porcine anterior cruciate ligament. J Orthop Res 25(1):81–91
31. Murray MM, Spindler KP, Ballard P, Welch TP, Zurakowski D, Nanney LB (2007) Enhanced histologic repair in a central wound in the anterior cruciate ligament with a collagen-platelet-rich plasma scaffold. J Orthop Res 25(8):1007–1017
32. Nagineni CN, Amiel D, Green MH, Berchuck M, Akeson WH (1992) Characterization of the intrinsic properties of the anterior cruciate and medial collateral ligament cells: an in vitro cell culture study. J Orthop Res 10(4):465–475
33. Nakase J, Tsuchiya H, Kitaoka K (2012) Contralateral anterior cruciate ligament injury after anterior cruciate ligament reconstruction: a case controlled study. Sports Med Arthrosc Rehabil Ther Technol 4(1):46
34. National Institutes of Health (NIH), National Institute of Arthritis and Musculoskeletal and Skin Diseases (NIAMS), Vanderbilt University, United States (n.d.) Prognosis and predictors of ACL reconstruction – a multicenter cohort study. http://clinicaltrials.gov/ct2/show/NCT00463099. Accessed 25 May 2015
35. Nishimoto S, Oyama T, Matsuda K (2007) Simultaneous concentration of platelets and marrow cells: a simple and useful technique to obtain source cells and growth factors for regenerative medicine. Wound Repair Regen 15(1):156–162
36. Noyes FR, Mooar LA, Moorman CT 3rd, McGinniss GH (1989) Partial tears of the anterior cruciate ligament progression to complete ligament deficiency. J Bone Joint Surg (Br) 71(5):825–833
37. O' Donoghue DH (1950) Surgical treatment of fresh injuries to the major ligaments of the knee. J Bone Joint Surg Am 32(A: 4):721–738
38. Papalia R, Franceschi F, Zampogna B, Tecame A, Maffulli N, Denaro V (2014) Surgical management of partial tears of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 22(1):154–165
39. Pitman MI, Nainzadeh N, Menche D, Gassalberti R, Song EK (1992) The intraoperative evaluation of the neurosensory function of the anterior cruciate ligament in humans using somatosensory evoked potentials. Arthroscopy 8(4):442–447
40. Pujol N, Colombet P, Cucurulo T, Graveleau N, Hulet C, Panisset JC, Potel JF, Servien E, Sonnery-Cottet B, Trojani C, Dijan P (2012) Natural history of partial anterior cruciate ligament tears: a systematic literature review. Orthop Traumatol Surg Res 98(8 Suppl):S160–S164
41. Pujol N, Colombet P, Potel JF, Cucurulo T, Graveleau N, Hulet C, Panisset JC, Servien E, Sonnery-Cottet B, Trojani C, Dijan P (2012) Anterior cruciate ligament reconstruction in partial tear: selective anteromedial bundle reconstruction conserving the posterolateral remnant versus single-bundle anatomic ACL reconstruction: preliminary 1-year results of a prospective randomized study. Orthop Traumatol Surg Res 98(8 Suppl):S171–S177
42. Robson AW (1903) Ruptured cruciate ligaments and their repair by operation. Ann Surg 37(5):716–718
43. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K (2005) Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthroscopy 21(8): 948–957
44. Scotti C, Gobbi A, Karnatzikos G, Martin I, Shimomura K, Lane JG, Peretti GM, Nakamura N (2016) Cartilage repair in the inflamed joint: considerations for biological augmentation toward tissue regeneration. Tissue Eng Part B Rev 22(2):149–159
45. Shelbourne KD, Klootwyk TE, Wilckens JH, De Carlo MS (1995) Ligament stability two to six years after anterior cruciate ligament reconstruction with autogenous patellar tendon graft and participation in accelerated rehabilitation program. Am J Sports Med 23(5):575–579
46. Sherman MF, Lieber L, Bonamo JR, Podesta L, Reiter I (1991) The long-term follow-up of primary anterior cruciate ligament repair. Defining a rationale for augmentation. Am J Sports Med 19(3):243–255
47. Spindler KP, Parker RD, Andrish JT, Kaeding CC, Wright RW, Marx RG, McCarty EC, Amendola A, Dunn WR, Huston LJ, Harrell FE Jr (2013) Prognosis and predictors of ACL reconstructions using the MOON cohort: a model for comparative effectiveness studies. J Orthop Res 31(1):2–9
48. Steadman JR, Cameron-Donaldson ML, Briggs KK, Rodkey WG (2006) A minimally invasive technique ("healing response") to treat proximal ACL injuries in skeletally immature athletes. J Knee Surg 19(1): 8–13
49. Steadman JR, Matheny LM, Briggs KK, Rodkey WG, Carreira DS (2012) Outcomes following healing response in older, active patients: a primary anterior cruciate ligament repair technique. J Knee Surg 25(3): 255–260
50. Steadman JR, Rodkey WG (1993) Role of primary anterior cruciate ligament repair with or without augmentation. Clin Sports Med 12(4):685–695
51. Steinert AF, Kunz M, Prager P, Barthel T, Jakob F, Noth U, Murray MM, Evans CH, Porter RM (2011) Mesenchymal stem cell characteristics of human anterior cruciate ligament outgrowth cells. Tissue Eng A 17(9–10):1375–1388
52. Vavken P, Murray MM (2010) Translational studies in ACL repair. Tissue Eng Rev 16(1):5–11
53. Vavken P, Murray MM (2011) The potential for primary repair of the ACL. Sports Med Arthrosc 19(1):44–49
54. Vavken P, Murray MM (2011) Treating anterior cruciate ligament tears in skeletally immature patients. Arthroscopy 27(5):704–716, Review
55. Von Porat A, Roos EM, Roos H (2004) High prevalence of osteoarthritis 14 years after an anterior

cruciate ligament tear in male soccer players: a study. Ann Rheum Dis 63(3):269–273

56. Wiig ME, Amiel D, Ivarsson M, Nagineni CN, Wallace CD, Arfors KE (1991) Type I procollagen gene expression in normal and early healing of the medial collateral and anterior cruciate ligaments in rabbits: an in situ hybridization study. J Orthop Res 9(3):374–382
57. Zastawna E, Drewniak W, Powierza W, Rosc D, Michalski A, Kotschy M (2002) Post-traumatic plasminogenesis in intraarticular exudate in the knee joint. Med Sci Monit 8:CR371–CR378

Selected Reading

Amiel D, Nagineni CN, Choi SH, Lee J (1995) Intrinsic properties of ACL and MCL cells and their responses to growth factors. Med Sci Sports Exerc 27(6): 844–851

Gobbi A, Bathan L, Boldrini L (2009) Primary repair combined with bone marrow stimulation in acute anterior cruciate ligament lesions: results in a group of athletes. Am J Sports Med 37:571–578

Gobbi A, Boldrini L, Karnatzikos G et al (2012) Clinical outcomes and rehabilitation program after ACL primary repair and bone marrow stimulation. In: Doral MN (ed) Sports Injuries-prevention, diagnosis, treatment and rehabilitation. Springer, Berlin, pp 475–484

Gobbi A, Karnatzikos G, Sankineani SR, Petrera M (2013) Biological augmentation of ACL re-fixation in partial lesions in a group of athletes: results at 5-year follow-up. Tech Orthop 28(2):180–184

Kaplan N, Wickiewicz TL, Warren RF (1990) Primary surgical treatment of anterior cruciate ligament ruptures: a long-term follow-up study. Am J Sports Med 18(4):354–358

Murray MM, Martin SD, Martin TL et al (2000) Histological changes in the human anterior cruciate ligament after rupture. J Bone Joint Surg Am 82-A(10): 1387–1397

Noyes FR, Mooar LA, Moorman CT 3rd et al (1989) Partial tears of the anterior cruciate ligament. Progression to complete ligament deficiency. J Bone Joint Surg (Br) 71(5):825–833

Steadman JR, Cameron-Donaldson ML, Briggs KK et al (2006) A minimally invasive technique (“healing response”) to treat proximal ACL injuries in skeletally immature athletes. J Knee Surg 19(1):8–13

Steadman JR, Matheny LM, Briggs KK et al (2012) Outcomes following healing response in older, active patients: a primary anterior cruciate ligament repair technique. J Knee Surg 25(3):255–260

Steinert AF, Kunz M, Prager P et al (2011) Mesenchymal stem cell characteristics of human anterior cruciate ligament outgrowth cells. Tissue Eng A 17(9–10): 1375–1388

Vavken P, Murray MM (2011) The potential for primary repair of the ACL. Sports Med Arthr 19(1):44–49

Meniscal Repair with ACL Reconstruction

14

Ryohei Uchida and Shuji Horibe

14.1 Meniscal Tears with ACL Injury

Approximately 26–60 % of patients with anterior cruciate ligament (ACL) injury have meniscal tears [14, 26, 34, 36]. In acute ACL injuries, the lateral meniscus is more frequently torn [6, 39], whereas the medial meniscus is more commonly damaged in chronic injuries. The medial meniscus is tightly attached to the tibia and is less mobile [39, 42] and has a stabilizing function conferred by the posterior horn, which acts as a mechanical wedge between the tibia and femur [27]. Therefore, the medial meniscus serves as a secondary restraint to anteroposterior tibial translation, which becomes more substantial with the loss of ACL function. The recurrent trauma sustained by the medial meniscus causes peripheral posterior tears while acting as a "bumper" in chronic ACL-insufficient knees [9, 20]. On the other hand, since the lateral meniscus is not tightly attached to the tibial plateau, a combination of unusual compressive and shear forces is applied during a twisting knee injury [6]. If the tibia subluxates anterolaterally in acute ACL injury, the lateral meniscus becomes trapped between the posterolateral aspect of the tibia and femoral condyle, resulting in a tear [11]. However, the lateral meniscus is not subject to recurrent anterior shear forces, because the lateral meniscus is more mobile than the medial meniscus. Considering these injury mechanisms, both medial and lateral meniscal tears associated with ACL injury are expected to locate frequently to the posterior region. According to a recent prospective analysis [36], peripheral tears accounted for 60.7 % (75.4 % of medial meniscus vs 44.1 % of lateral meniscus) of all tears, and 93.9 % of all tears involved the posterior region (99.4 % of medial meniscus vs 87.8 % of lateral meniscus). In a systematic review that assessed tear location with ACL injury, 83.6 % of tears were located in the posterior region, and 65.6 % of tears in the peripheral region [5]. The incidence of peripheral posterior tears was 60–65 % (48–75 % of medial meniscus and 43 % of lateral meniscus) [9, 20, 36]. In terms of tear patterns, the rate of longitudinal tears is the highest at 84 %, followed by bucket-handle tears at 10 % [44].

14.2 Indication

Indications for meniscal repair are essentially the same for patients with or without ACL reconstruction (ACLR). The decision is made by

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considering arthroscopic findings during ACLR, including tear location, tear length, tear pattern, and condition of the meniscal body. In terms of tear location, red-red and red-white tears should be repaired, as there is sufficient vascularity to heal these regions. Red-white tears occur at the junction of the outer- and middle-third regions, approximately 4 mm from the meniscal attachment. In red-red and red-white regions, tears of more than 1 cm, as well as unstable tears, are indicated for meniscal repair. Unstable tears are defined as those that could be displaced beyond the femoral condyle by probing.

Regarding tear patterns, longitudinal and oblique tears are the most amenable to repair, whereas radial and horizontal tears, including complex tears with radial components, are less amenable due to the tears being in regions with poor vascularity. The macroscopic meniscal body may affect treatment decisions. Horibe et al. [19] suggested that the condition of the meniscal body at the time of repair affects the clinical outcome and reported poor results of meniscal repair for menisci with abnormal bodies, concluding that meniscal body condition at repair is an important consideration.

Meniscal repair is generally performed simultaneously with ACLR, regardless of whether the ACL injury is acute or chronic. However, a two-stage procedure may be considered for ACL injury patients with extension loss due to a locked meniscus. If a two-stage approach is selected, extension exercises should be performed after initial arthroscopic treatment (meniscectomy or reduction of locked knee) for a locked meniscus, and once full extension is regained, this can be followed by staged ACLR.

At the posterior horn of the lateral meniscus, various tear patterns are observed in ACL-deficient knees. Tears in this region appear to have a higher chance of healing or remain asymptomatic compared with medial meniscal tears. Indeed, stable posterior horn tears in situ during ACLR have a high rate of complete healing and clinical success [15, 25]. Moreover, rasping and trephination are also effective for treating stable posterior horn tears [41]. One reason for the high healing potential of lateral meniscal tears at the posterior horn is that this region is more vascularized than the medial and lateral meniscal body [10]. Another reason is that the occurrence of hematoma and bleeding from bone marrow during ACLR may enhance the healing of lateral meniscal tears [16]. Thus, repair is not absolutely necessary for stable posterior horn tears in the lateral meniscus.

In skeletally immature patients, the treatment of meniscal tears with concomitant ACL rupture is important. ACL insufficiency impairs the healing of meniscal tears [22], and loss of meniscal tissue is associated with a poor prognosis for children with a high risk of future joint arthrosis [30]. Thus, meniscal repair should be performed at the time of ACLR using techniques adapted to skeletally immature patients [1, 18, 35]. Yet, one must also keep in mind that ACLR in these patients can potentially lead to growth disturbances.

14.3 Surgical Technique

Most meniscal tears associated with ACL tears are longitudinal and located in the peripheral posterior region. Smith et al. [36] recommended that peripheral posterior tears should be treated with an inside-out repair which allows for secure fixation to the capsule. Inside-out vertical mattress suture repair has also superior biomechanical properties compared with most all-inside devices and horizontal sutures [13], although newer all-inside devices are biomechanically equivalent to suture repair [4].

Our preferred procedure is an inside-out “double-stacked vertical divergent suture repair” technique for meniscal repair associated with ACL injuries (Fig. 14.1) [29]. The technique involves making a skin incision, 3–4 cm long, along the posterior border of collateral ligaments. Under arthroscopic control, the parasynovial tissue at the tear site is meticulously abraded with a rasp. Multiple nonabsorbable sutures are placed vertically every 5 mm in the tear in a stacked manner so that the torn meniscus is fixed firmly to the capsule using a retractor that protects the

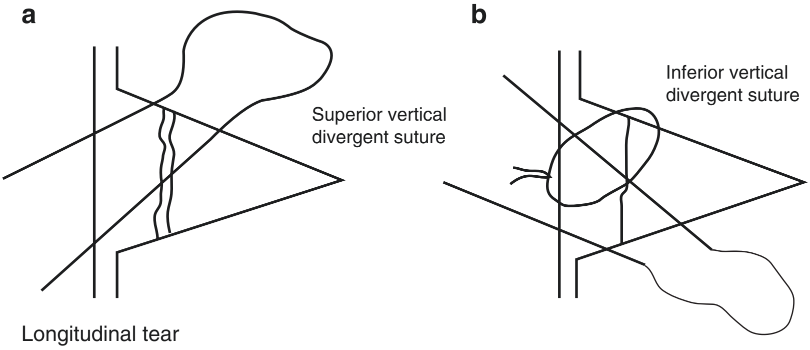

Fig. 14.1 Double-stacked vertical divergent suture repair of single longitudinal meniscal tear [30]. (**a**) The first pass of the suture is placed into the peripheral portion of the tear. (**b**) The second pass is placed vertically through the central one-third region

posterior neurovascular bundle. These sutures reduce the meniscus to its anatomic attachment site and ensure that the superior surface does not displace when the cannula is later placed beneath the meniscus for placement of inferior sutures on the tibial surface. New useful suture materials for inside-out repair have been developed, including Polyester Mesh Plate® ("Fettuccine"; Matsudaika Kogyo Co., Ltd., Tokyo, Japan) and Hollow Polyester Suture 2-0® ("Macaroni"; Matsudaika Kogyo Co., Ltd., Tokyo, Japan) (Figs. 14.2, 14.3, and 14.4).

14.4 Clinical Outcomes

Many studies have reported on clinical outcomes after meniscal repair, but these studies usually included the patients with and without ACL injury. Only a few studies have specifically targeted cases of meniscal repair with concurrent ACLR. At early follow-up (2 years), high success rates have been reported (90–96 %) [40, 43], whereas long-term studies show a decline in success rates with time [24, 44]. Long-term outcomes after meniscal repair in patients undergoing concurrent ACLR are limited to case series, with failure rates ranging from 0 % to 29 % at a minimum of 5 years of follow-up [24, 28, 38]. A recent systematic review calculated the failure rate of meniscal repair with ACLR to be 26.9 % at 5 years [32]. In addition to these studies, those that have assessed prognostic factors affecting the outcomes of meniscal repair with concomitant ACL injury have been published. Generally, tear location and joint stability are factors that affect meniscal healing [8, 37, 44]. However, other factors such as tear length and pattern, patient age, repair technique, and chronicity of the injury may also affect healing [5, 37, 44].

With respect to tear location, meniscal repair of red-red and red-white tears is associated with acceptable short- and midterm clinical healing rates with or without ACLR. Although limited information regarding meniscal repair in avascular regions exists, white-white tears had a lower rate of complete meniscal healing when evaluated by second arthroscopy than red-red or red-white tears in short-term follow-up studies [2, 8].

In ACL-insufficient knees, microdamage can explain increasing rates of medial meniscal lesions [37]. The rate of secondary meniscectomy after meniscal repair in unstable knees was higher than that in ACL reconstructed knees [38]. Most investigators noted that one of the most important factors for meniscal healing is the restoration of joint stability. This suggests the need to perform ACLR with anatomical tunnel placement in order to restore normal anterior laxity.

In a comparison of clinical outcomes of meniscal repair between ACL reconstructed, insufficient, and intact knees, outcomes for reconstructed knees were better [3, 17, 21, 23, 33]. There are three possible explanations for the improved success of meniscal repair with concurrent ACLR. First, drilling of tibial and femoral tunnels and the associated bleeding may promote a biologically favorable environment for meniscal healing [43]. Second, slower rehabilitation of patients undergoing ACLR promotes a low-force

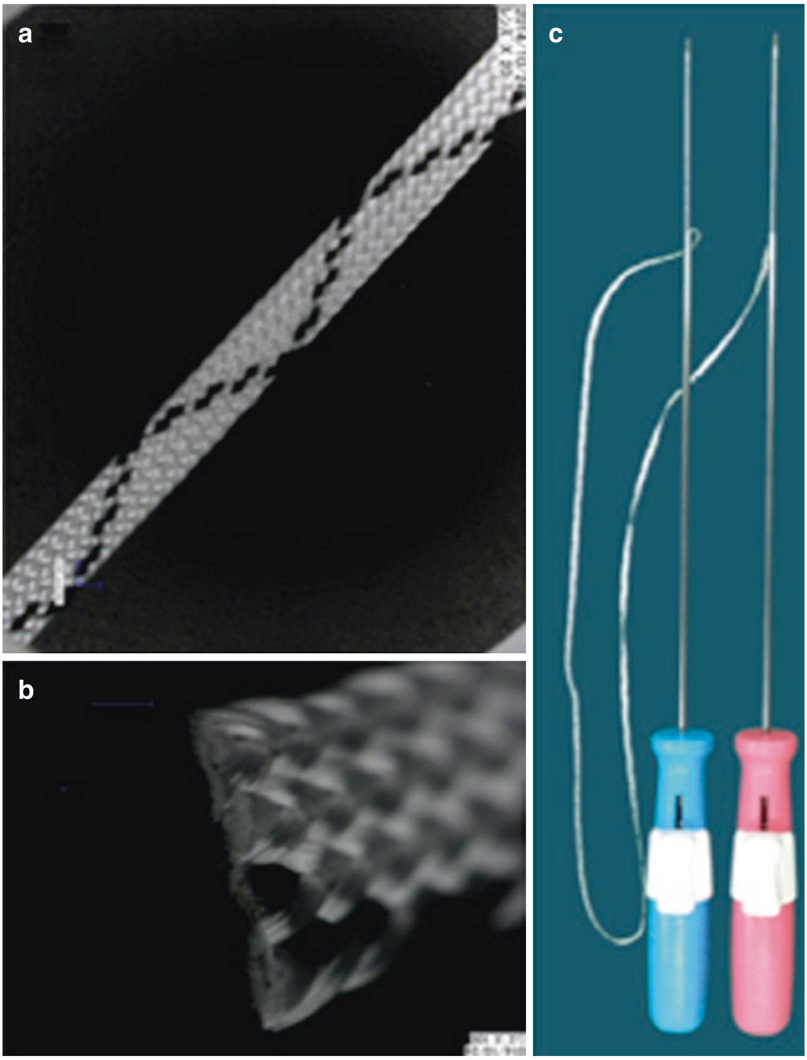

Fig. 14.2 Polyester Mesh®, “Fettuccine.” (**a**) Macroscopic appearance of polyester mesh. (**b**) Magnified photograph of cross-section surface. (**c**) A suture kit with polyester mesh

environment for the meniscus. Third, the tear pattern of meniscus with acute ACL rupture may be more amenable to repair [7, 32], whereas injured menisci in intact knees are more commonly degenerative [12, 31].

Although grafts used for ACLR do not significantly influence the failure rate of meniscal repair, the condition of the transplanted graft affects the outcome of the repaired meniscus. Indeed, a large proportion of meniscal failures (27.3 %) are associated with ACL graft failure [44].

14.5 Summary

Progress has been made recently in surgical strategies for meniscal repair, which have substantially improved clinical outcomes. Yet, some negative prognostic factors exist for meniscal healing in cases of ACLR. Considering the importance of restoring knee joint kinematics for facilitating meniscal healing environment following ACLR, it is likely important to consider anatomical reconstruction of the ACL.

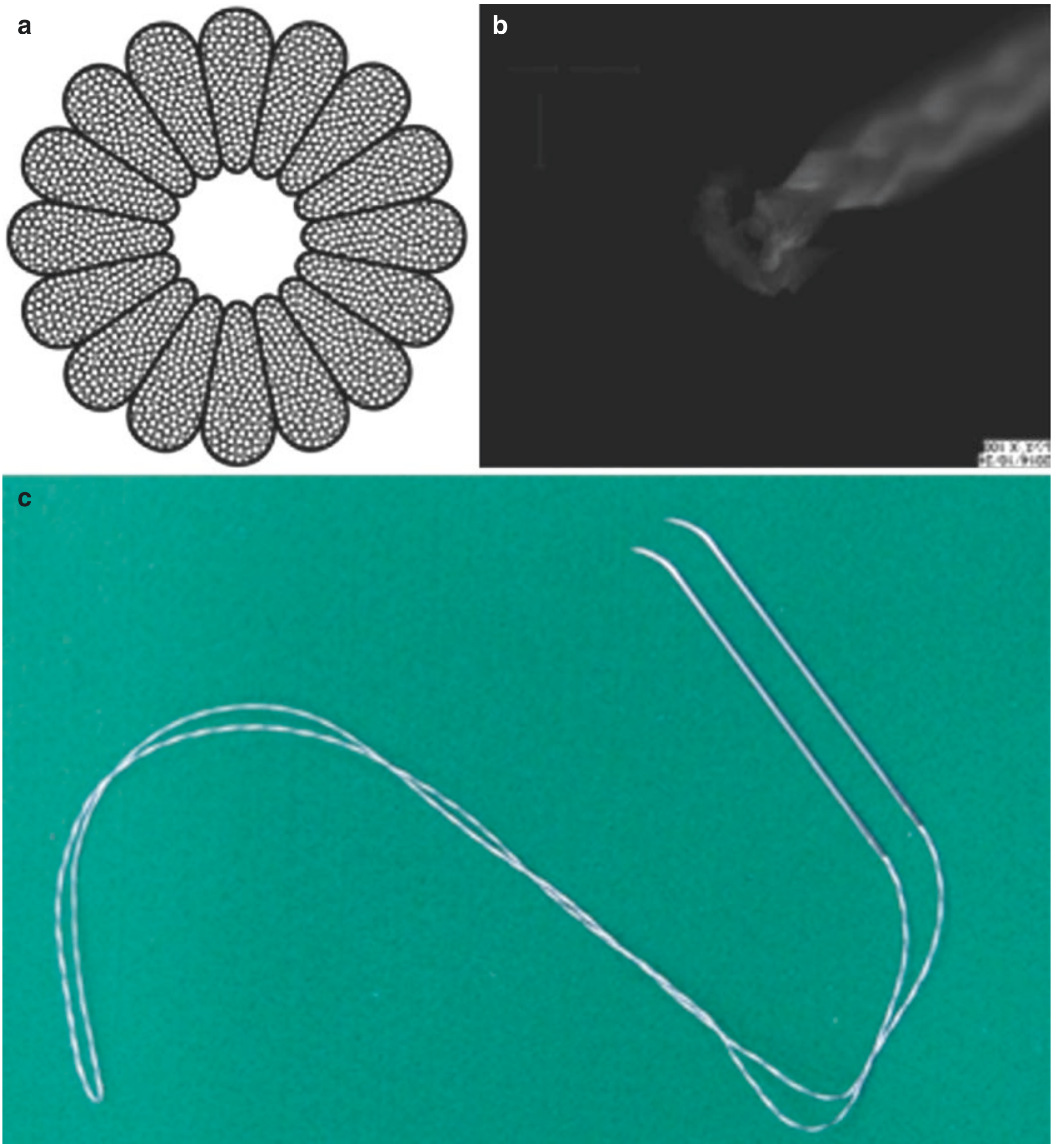

Fig. 14.3 Hollow Polyester Suture 2-0®, "Macaroni." (**a**) Diagram of cross-section surface. (**b**) Magnified photograph of cross-section surface. (**c**) A suture kit with Hollow Polyester Suture 2-0

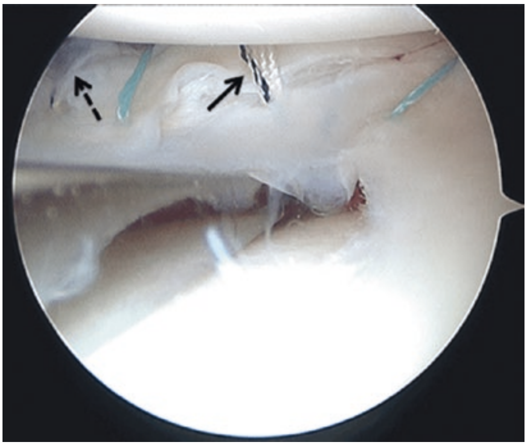

Fig. 14.4 Arthroscopic view of inside-out meniscal repair using new suture materials Polyester Mesh®, "Fettuccine" (*black arrow*), and Hollow Polyester Suture 2-0®, "Macaroni" (*dotted black arrow*)

References

1. Anderson AF (2003) Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. J Bone Joint Surg Am 85:1255–1263
2. Asahina S, Muneta T, Yamamoto H (1996) Arthroscopic meniscal repair in conjunction with anterior cruciate ligament reconstruction: factors affecting the healing rate. Arthroscopy 12:541–545
3. Asik M, Sen C, Erginsu M (2002) Arthroscopic meniscal repair using T-fix. Knee Surg Sports Traumatol Arthrosc 10:284–288
4. Barber FA, Herbert MA, Bava ED, Drew OR (2012) Biomechanical testing of suture-based meniscal repair devices containing ultrahigh-molecular-weight polyethylene suture: update 2011. Arthroscopy 28:827–834
5. Barber-Westin SD, Noyes FR (2014) Clinical healing rates of meniscus repairs of tears in the central-third (red-white) zone. Arthroscopy 30:134–146
6. Bellabarba C, Bush-Joseph CA, Bach BR Jr (1997) Patterns of meniscal injury in the anterior cruciate-deficient knee: a review of the literature. Am J Orthop 26:18–23
7. Belzer JP, Cannon WD Jr (1993) Meniscus tears: treatment in the stable and unstable knee. J Am Acad Orthop Surg 1:41–47
8. Buseck MS, Noyes FR (1991) Arthroscopic evaluation of meniscal repairs after anterior cruciate ligament reconstruction and immediate motion. Am J Sports Med 19:489–494
9. Cerabona F, Sherman MF, Bonamo JR et al (1988) Patterns of meniscal injury with acute anterior cruciate ligament tears. Am J Sports Med 16:603–609
10. Day B, Mackenzie WG, Shim SS, Leung G (1985) The vascular and nerve supply of the human meniscus. Arthroscopy 1:58–62
11. Duncan JB, Hunter R, Purnell M, Freeman J (1995) Meniscal injuries associated with acute anterior cruciate ligament tears in alpine skiers. Am J Sports Med 23:170–172
12. Eggli S, Wegmuller H, Kosina J, Huckell C, Jakob RP (1995) Long-term results of arthroscopic meniscal repair: an analysis of isolated tears. Am J Sports Med 23:715–720
13. Farng E, Sherman O (2004) Meniscal repair devices: a clinical and biomechanical literature review. Arthroscopy 20:273–286
14. Fetzer GB, Spindler KP, Amendola A et al (2009) Potential market for new meniscus repair strategies: evaluation of the MOON cohort. J Knee Surg 22: 180–186
15. Fitzgibbons RE, Shelbourne KD (1995) "Aggressive" nontreatment of lateral meniscal tears seen during anterior cruciate ligament reconstruction. Am J Sports Med 23:156–159
16. Foad A (2012) Self-limited healing of a radial tear of the lateral meniscus. Knee Surg Sports Traumatol Arthrosc 20:933–936
17. Frosch KH, Fuchs M, Losch A, Stürmer KM (2005) Repair of meniscal tears with the absorbable clearfix screw: results after 1-3 years. Arch Orthop Trauma Surg 125:585–591
18. Fuchs R, Wheatley W, Uribe JW, Hechtman KS, Zvijac JE, Schurhoff MR (2002) Intra-articular anterior cruciate ligament reconstruction using patellar tendon allograft in the skeletally immature patient. Arthroscopy 18:824–828
19. Horibe S, Shino K, Nakata K, Maeda A, Nakamura N, Matsumoto N (1995) Second-look arthroscopy after meniscal repair. Review of 132 menisci repaired by an arthroscopic inside-out technique. J Bone Joint Surg (Br) 77:245–249
20. Indelicato PA, Bittar ES (1985) A perspective of lesions associated with ACL insufficiency of the knee: a review of 100 cases. Clin Orthop 198:77–80
21. Keene GC, Bickerstaff D, Rae PJ, Paterson RS (1993) The natural history of meniscal tears in anterior cruciate ligament insufficiency. Am J Sports Med 21:672–679
22. Kimura M, Shirakura K, Hasegawa A, Kobuna Y, Niijima M (1995) Second look arthroscopy after meniscal repair. Factors affecting the healing rate. Clin Orthop Relat Res 314:185–191
23. Kocabey Y, Nyland J, Isbell WM, Caborn DNM (2004) Patient outcomes following T-Fix meniscal repair and a modifiable, progressive rehabilitation program, a retrospective study. Arch Orthop Trauma Surg 124:592–596
24. Lee GP, Diduch DR (2005) Deteriorating outcomes after meniscal repair using the meniscus arrow in knees undergoing concurrent anterior cruciate ligament reconstruction: increased failure rate with long-term follow-up. Am J Sports Med 33:1138–1141
25. Lee DW, Jang HW, Lee SR, Park JH, Ha JK, Kim JG (2014) Clinical, radiological, and morphological evaluations of posterior horn tears of the lateral meniscus left in situ during anterior cruciate ligament reconstruction. Am J Sports Med 42:327–335

26. Levy AS, Meier SW (2003) Approach to cartilage injury in the anterior cruciate ligament-deficient knee. Orthop Clin North Am 34:149–167
27. Levy IM, Torzilli PA, Warren RF (1982) The effect of medial meniscectomy on anterior-posterior motion of the knee. J Bone Joint Surg 64:883–888
28. Logan M, Watts M, Owen J, Myers P (2009) Meniscal repair in the elite athlete: results of 45 repairs with a minimum 5-year follow-up. Am J Sports Med 37:1131–1134
29. McLaughlin JR, Noyes FR (1993) Arthroscopic meniscus repair: recommended surgical techniques for complex meniscal tears. Tech Orthop 8:129–136
30. McNicholas MJ, Rowley DI, McGurty D et al (2000) Total meniscectomy in adolescence. A thirty-year follow-up. J Bone Joint Surg (Br) 82:217–221
31. Meister K, Indelicato PA, Spanier S, Franklin J, Batts J (2004) Histology of the torn meniscus: a comparison of histologic differences in meniscal tissue between tears in anterior cruciate ligament-intact and anterior cruciate ligament-deficient knees. Am J Sports Med 32:1479–1483
32. Nepple JJ, Dunn WR, Wright RW (2012) Meniscal repair outcomes at greater than five years: a systematic literature review and meta-analysis. J Bone Joint Surg Am 94:2222–2227
33. Noyes FR, Barber-Westin SD (2000) Arthroscopic repair of meniscus tears extending into the avascular zone with or without anterior cruciate ligament reconstruction in patients 40 years of age and older. Arthroscopy 16:822–829
34. Noyes FR, Barber-Westin SD (2012) Treatment of meniscus tears during anterior cruciate ligament reconstruction. Arthroscopy 28:123–130
35. Robert H, Bonnard C (1999) The possibilities of using the patellar tendon in the treatment of anterior cruciate ligament tears in children. Arthroscopy 15:73–76
36. Smith JP, Barrett GR (2001) Medial and lateral meniscal tear patterns in anterior cruciate ligament-deficient knees. A prospective analysis of 575 tears. Am J Sports Med 29:415–419
37. Stärke C, Kopf S, Petersen W, Becker R (2009) Meniscal repair. Arthroscopy 25:1033–1044
38. Steenbrugge F, Verdonk R, Hurel C, Verstraete K (2004) Arthroscopic meniscus repair: inside-out technique vs. Biofix meniscus arrow. Knee Surg Sports Traumatol Arthrosc 12:43–49
39. Thompson WO, Fu FH (1993) The meniscus in the cruciate-deficient knee. Clin Sports Med 12:771–796
40. Toman CV, Dunn WR, Spindler KP et al (2009) Success of meniscal repair at anterior cruciate ligament reconstruction. Am J Sports Med 37:1111–1115
41. Uchio Y, Ochi M, Adachi N, Kawasaki K, Iwasa J (2003) Results of rasping of meniscal tears with and without anterior cruciate ligament injury as evaluated by second-look arthroscopy. Arthroscopy 19:463–469
42. Warren LF, Marshall JL (1979) The supporting structures and layers on the medial side of the knee: an anatomical analysis. J Bone Joint Surg 61:56–62
43. Wasserstein D, Dwyer T, Gandhi R, Austin PC, Mahomed N, Ogilvie-Harris D (2013) A matched-cohort population study of reoperation after meniscal repair with and without concomitant anterior cruciate ligament reconstruction. Am J Sports Med 41:349–355
44. Westermann RW, Wright RW, Spindler KP, Huston LJ, MOON Knee Group, Wolf BR (2014) Meniscal repair with concurrent anterior cruciate ligament reconstruction: operative success and patient outcomes at 6-year follow-up. Am J Sports Med 42: 2184–2192

Anatomy of ACL Insertion: Ribbon

15

Robert Śmigielski and Urszula Zdanowicz

15.1 Femoral Insertion

Śmigielski et al. [7, 9] in his anatomical dissection of 111 fresh-frozen cadaveric knees (from 81 people) evaluated in detail the femoral insertion site of the anterior cruciate ligament (ACL). All degenerative knees (with fourth-degree chondromalacia) were excluded from the study. There were 45 males and 36 females. The mean age was 67 and mean BMI 22,6. After carefully removing the synovial membrane that covers the ACL, flat, “ribbonlike” appearance of the anterior cruciate ligament was clearly seen (Fig. 15.1). This flat appearance was also confirmed in MRI and CT scan as well as in histology evaluation.

This flat appearance was also noted in several previous papers.

In 1980, Welsh [10] describes that femoral ACL attachment “inserts into a broad flat area on the back of the lateral femoral condyle.” It inserts “not as a distinct cord but is splayed over a broad flattened area.”

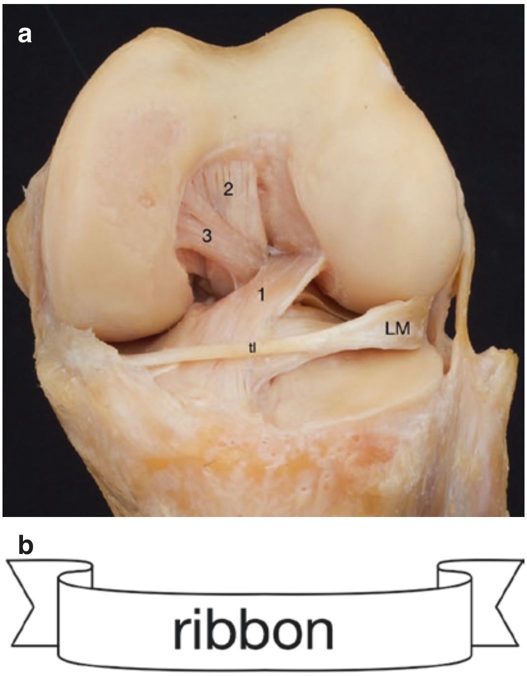

Fig. 15.1 (**a**) Cadaveric specimen of human left knee joint. (*1*) Anterior cruciate ligament (ACL). Notice: flat and wide, “ribbonlike” appearance of ACL. (*2*) Posterior cruciate ligament (PCL). (*3*) Anterior menisco-femoral ligament. *LM* lateral meniscus, *tl* transverse ligament. (**b**) Schema of “ribbon shape.” Some authors also compare this shape of ACL to “lasagna,” “pappardelle,” “fettuccine” or “kishimen” pasta

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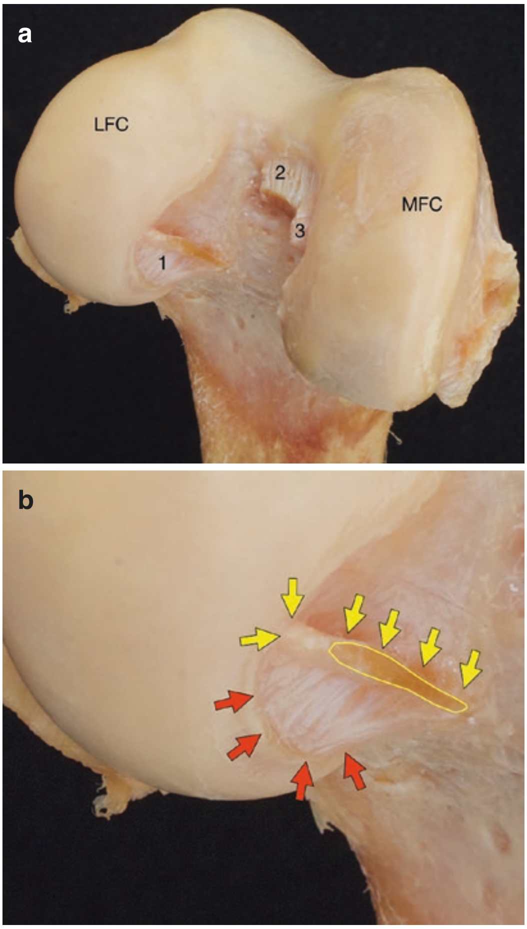


Fig. 15.2 (**a**) Cadaveric specimen of human right distal femur. *LFC* lateral femoral condyle, *MFC* medial femoral condyle. (*1*) ACL. (*2*) PCL. (*3*) Anterior menisco-femoral ligament. (**b**) Close look to femoral ACL attachment. Notice: Fanlike fibers marked with *red arrows*. Midsubstance fibers marked with *yellow arrows*. Own material

In 2013, Mochizuki et al. [4] published a paper in which he evaluates anatomical appearance of fanlike extension fibers at the femoral ACL attachment site in 28 cadaveric knees. He distinguished between direct and indirect insertion, based on histological appearance. Direct insertion (midsubstance fibers) has a transitional cartilaginous zone through which ACL fibers attach to the bone. That kind of insertion is typical for areas with great tension applied. The indirect insertion is created by fanlike extension fibers which are directly attached to the bone (Fig. 15.2a, b).

The attachment of midsubstance fibers of ACL is in exact continuity of the posterior femoral cortex [7, 9] (Fig. 15.3a–c). Knowing that relationship, the surgeon may double check the position of his femoral tunnel: arthroscopically and intraoperatively with X-ray C-arm. However, one may not talk about tunnel placement without a context of graft and fixation choice (Fig. 15.4a–c). For example, the use of BPTB graft or even a hamstring graft with interference screw fixation allows to “push” the graft to the side of the tunnel. Therefore, if the graft is supposed to arise from the place where midsubstance ACL fibers have their direct attachment, the center of tunnel drilled should be a little “higher” (more toward ventral side).

15.2 Midsubstance

Early studies by Arnoczky [2] and Welsh [10] describe the midsubstance of the ACL to have multifascicular structure. In his study, Welsh describes that the midsubstance of ACL turns 90°. He also points out that this is functionally of great importance, because whatever the position of the knee would be (extension or flexion), some portions of ligament remain functional and under tension. Welsh goes further and stated that even though ACL consists of two parts – anteromedial band and posterolateral band – that division would be oversimplification, because the ligament is not made up of two parts, but is a continuum of fibers with a broad insertion. This turning of the ligament and a broad flattening at the insertion means that ACL is truly isometric with actual lengthening or shortening of the ligament during knee movement, but rather tightening of different components within the ligament through different phases of range of motion.

In 1998, Amis et al. [1] also describes this twisting nature of midsubstance of ACL. The twist is unwounded as the knee extends and the fibers remain almost parallel in full extension (Fig. 15.5).

In 2006, in times when nobody really considered ACL to be literally flat, Mochizuki et al. [5]

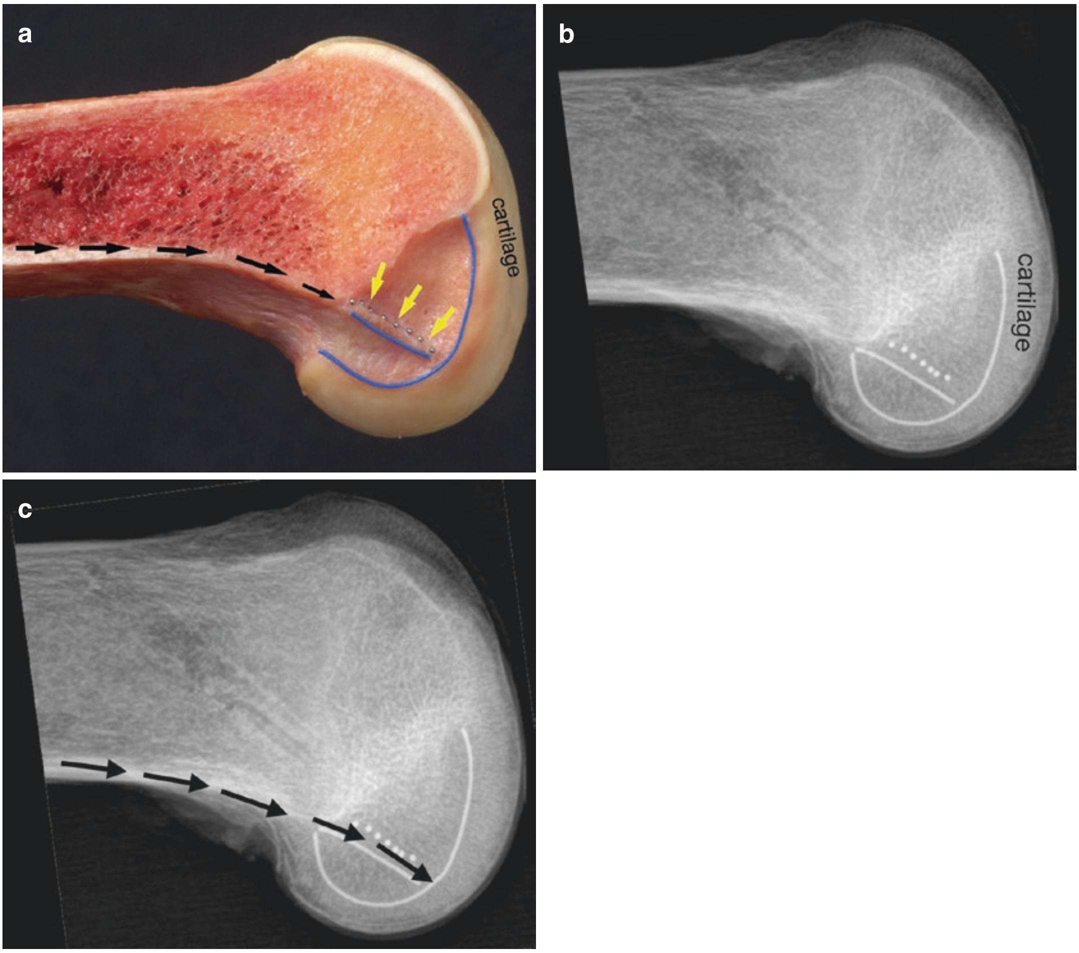


Fig. 15.3 (**a**) Cadaveric specimen of the left human distal femur. Medial view on the lateral femoral condyle, after removing (longitudinal cut) of medial femoral condyle. Posterior femoral cortex is marked with *black arrows*. The direct insertion of midsubstance fibers of ACL (marked with *yellow arrows*) is in line with posterior femoral cortex. *Blue suture marks* the borderline of articular cartilage and dorsal borderline of direct ACL insertion. *Silver balls mark* the ventral borderline of direct ACL insertion. (**b**, **c**) Same specimen, lateral X-ray. Notice relationship of direct midsubstance ACL fibers to posterior femoral cortex. Intraoperative X-ray allows for better control of correct localization of tunnel placement

published a paper describing an anatomical femoral tunnel placement of “double-bundle” ACL. In this paper, he noticed that “the configuration of the natural ACL midsubstance was not oval, but rather flat, looking like ‘lasagna’ about 15 mm in length and about 5 mm in width after removing of the surface membrane.” Also while carefully evaluating his picture documentation of the cadaver study, this flat ACL appearance is clearly visible.

15.3 Tibial Insertion

The anterior cruciate ligament arise from the tibia forming a “C” shape (Fig. 15.6a, b). It was first presented by Śmigielski in 2012 during ACL Study Group meeting (“The Ribbon Concept of the Anterior Cruciate Ligament”; Presentation at the ACL Study Group Meeting 2012, Jackson Hole, Wyoming, USA) and later confirmed by other researchers [6–8]. Researchers also describe

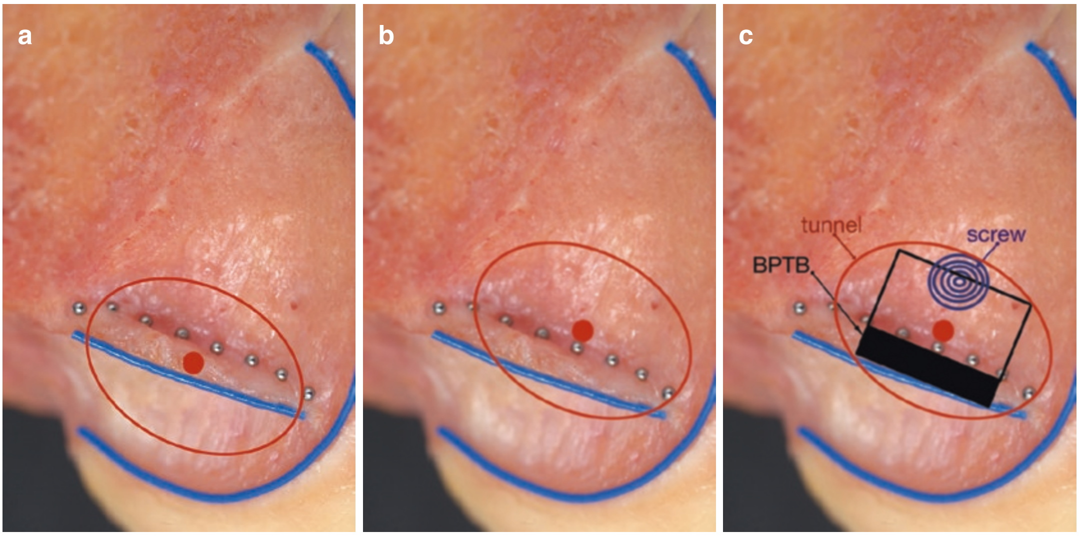


Fig. 15.4 Close look on ACL femoral insertion site. While choosing a perfect spot to drill your tunnel, you must think about your choice of graft and the fixation. In case of hamstring graft and Endo-button fixation, (**a**) your graft will arise from more or less the center of your tunnel, so the center should be at the level of the direct attachment of ACL midsubstance fibers. On the other hand, in cases of BPTB graft or a hamstring graft with an interference screw fixation, the screw will push your graft to the side of your tunnel (**b**, **c**), so your tunnel center should be little above the direct midsubstance ACL attachment

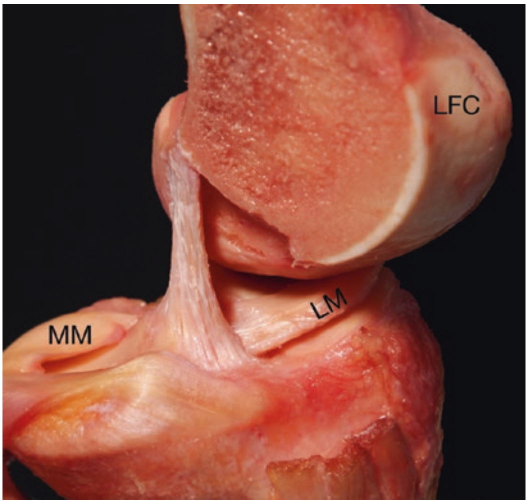


Fig. 15.5 Cadaveric specimen of the left knee joint. Medial femoral condyle is removed. *LFC* lateral femoral condyle, *LM* lateral meniscus, *MM* medial meniscus. Notice the way ACL is positioned in sagittal plane in knee extension. Compare the horizontal ACL arrangement with Fig. 15.1 (knee in flexion). Thanks to that phenomenon even a narrow intercondylar notch has enough space for ACL

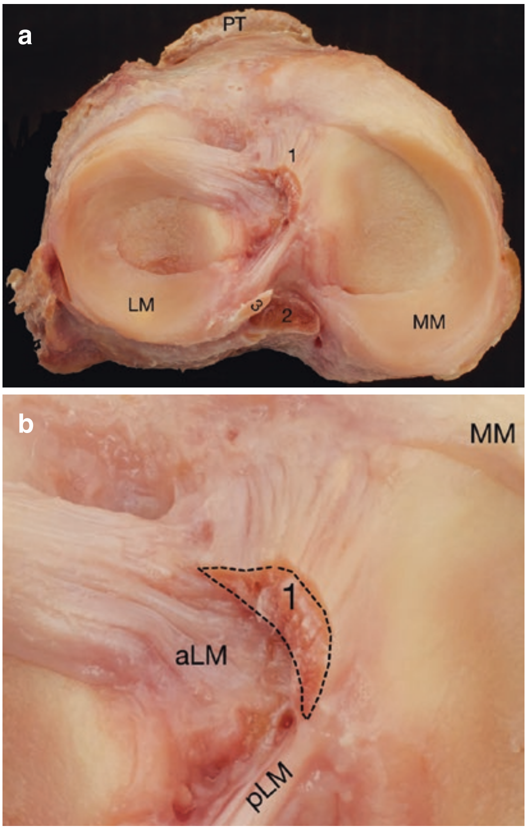
the distal part of ACL as of appearance of a "duck-foot".

One of the most interesting findings is the relationship between ACL tibial attachment and anterior horn of lateral meniscus. With the knee in flexion, as observed during arthroscopy. ACL passes backward, "laying over," covering the anterior horn of the lateral meniscus. That information has very practical consequences for surgeons drilling tibial tunnels for ACL reconstruction – to have in mind topographic anatomy and try not to destroy lateral meniscus.

Śmigielski et al. also observed three different types of the ACL tibial insertion: 67 % of specimens had a classical C-shaped tibial insertion site, 24 % J-shaped, and 9 % Cc-shaped (as presented by Śmigielski in 2012 during ACL Study Group, not published data).

The histological cross section of ACL tibial attachment allows for additional better understanding of ACL anatomy in this area. Oka et al. [6] stated that, in contrast to previous findings, functional midsubstance ACL fibers arise from the most posterior part of the "duck-foot," in a flat, "C-shaped" way. The most anterior part of the tibial ACL insertion is bordered by a bony anterior ridge and the most medial by the medial tibial spine. No posterolateral fibers nor ACL bundles have been found histologically (Fig. 15.7).

Fig. 15.6 (**a**) Cadaveric specimen of the left knee joint, femur removed. *1* ACL. *2* PCL. *3* anterior menisco-fibular ligament. *LM* lateral meniscus, *MM* medial meniscus, *PT* patellar tendon. (**b**) Closer look at tibial ACL attachment. *aLM* anterior horn of lateral meniscus, *pLM* posterior horn of lateral meniscus. Notice the way ACL arise from tibia forming a “C” shape and the way it surrounds anterior horn of lateral meniscus



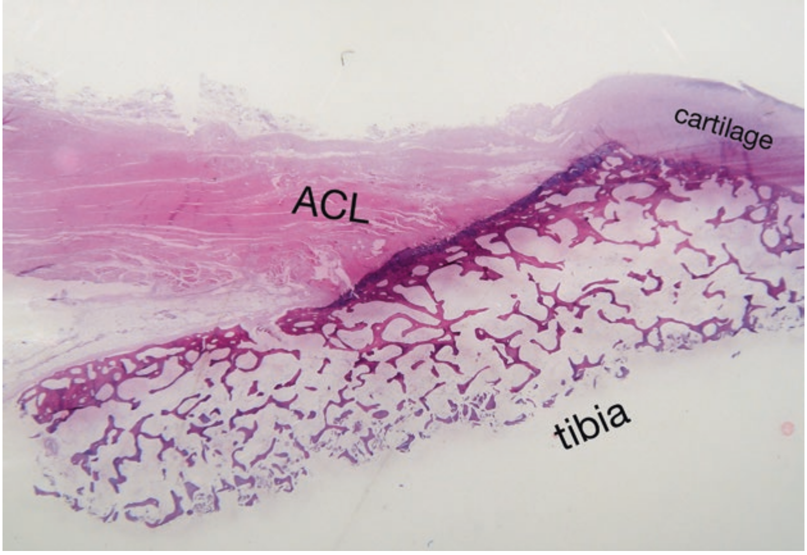


Fig. 15.7 Histology of the tibial ACL insertion (light microscopy, H&E stain)

15.4 Summary

In summary, it is the best to quote after John Feagin [3]: “Understand, respect and restore anatomy as much as possible.”

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References

1. Amis A, Jakob R (1998) Anterior cruciate ligament graft positioning, tensioning and twisting. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 6:S2–S12
2. Arnoczky SP (1983) Anatomy of the anterior cruciate ligament. Clin Orthop Relat Res (172):19–25
3. Feagin J, Hirschmann MT, Müller W (2015) Understand, respect and restore anatomy as close as possible! Knee Surg Sports Traumatol Artrosc: Off J ESSKA 23(10):2771–2772
4. Mochizuki T, Fujishiro H, Nimura A, Mahakkanukrauh P, Yasuda K, Muneta T, Akita K (2014) Anatomic and histologic analysis of the mid-substance and fan-like extension fibres of the anterior cruciate ligament during knee motion, with special reference to the femoral attachment. Knee Surg Sports Traumatol Artrosc: Off J ESSKA 22(2):336–344
5. Mochizuki T, Muneta T, Nagase T, Shirasawa S, Akita KI, Sekiya I (2006) Cadaveric knee observation study for describing anatomic femoral tunnel placement for two-bundle anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 22(4):356–361
6. Oka S, Schuhmacher P, Brehmer A, Traut U, Kirsch J, Siebold R (2016) Histological analysis of the tibial anterior cruciate ligament insertion. Knee Surg Sports Traumatol Artrosc Off J ESSKA 24(3):747–53
7. Siebold R, Dejour D, Zaffagnini S (2014a) Anterior cruciate ligament reconstruction: a practical surgical guide 19–35
8. Siebold R, Schuhmacher P, Fernandez F, Śmigielski R, Fink C, Brehmer A, Kirsch J (2014b) Flat midsubstance of the anterior cruciate ligament with tibial “C”-shaped insertion site. Knee Surg Sports Traumatol Artrosc Off J ESSKA 1–7
9. Śmigielski R, Zdanowicz U, Drwięga M, Ciszek B, Ciszkowska-Łysoń B, Siebold R (2014) Ribbon like appearance of the midsubstance fibres of the anterior cruciate ligament close to its femoral insertion site: a cadaveric study including 111. Knee Surg Sports Traumatol Artrosc Off J ESSKA 1–8
10. Welsh RP (1980) Knee joint structure and function. Clin Orthop Relat Res (147):7–14

Anatomy of ACL Insertion: Bundles

16

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16.1 Introduction

Over the past decades, great importance has been placed on the anterior cruciate ligament (ACL) anatomy due to the discussion about its reconstruction techniques. Literature shows better results with double-bundle procedure compared with single bundle [1–4]. However, it is a consensus that regardless of the surgical procedure used, the key for ACL reconstruction is the anterior cruciate ligament anatomy [3]. Odesten and Gillquist studied 33 cadaver knees and could find no macroscopic or microscopic evidence of subdivisions of the anterior cruciate ligament [5]. In their classical article, Girgis et al. found two distinct bundles: one anteromedial (AM) and one main posterolateral (PL) bundle [6]. Some authors showed three functional bundles: anteromedial, posterolateral, and one intermediate bundle [7–9]. Other authors observed that the "double-bundle effect" was created by the twisted flat ribbonlike structure of the ACL, which leads to the impression of two or three bundles as the knee was flexed [10]. This would confirm what Amis and Dawkins concluded that the multifascicular structure of the ACL can be described in bundles, although these are not necessarily separate fibers [7, 11, 12]. Despite this controversy, the concept that the ACL consists of two functional bundles is well accepted [1, 6, 7, 13–18].

16.2 The Anterior Cruciate Ligament

The ACL courses anteriorly, medially, and distally from the lateral condyle of the femur across the knee and reaches the tibial plateau [6]. Its average length and width are 31–38 mm [5, 6] and 11 mm [6], respectively. The ACL insertions are 3.5 times larger than the midsubstance of the ligament [15].

The morphology of the ACL midsubstance looks oval, with the surface membrane that covers the ligament. Near to the femoral and tibial insertion, the ligament fans out to take form of its broad footprint area. After the removal of the surface tissue, the morphology of the ACL midsubstance is not oval; it is flat, looking like "lasagna," with about 15 mm in length [19] and 5 mm in width [19, 20].

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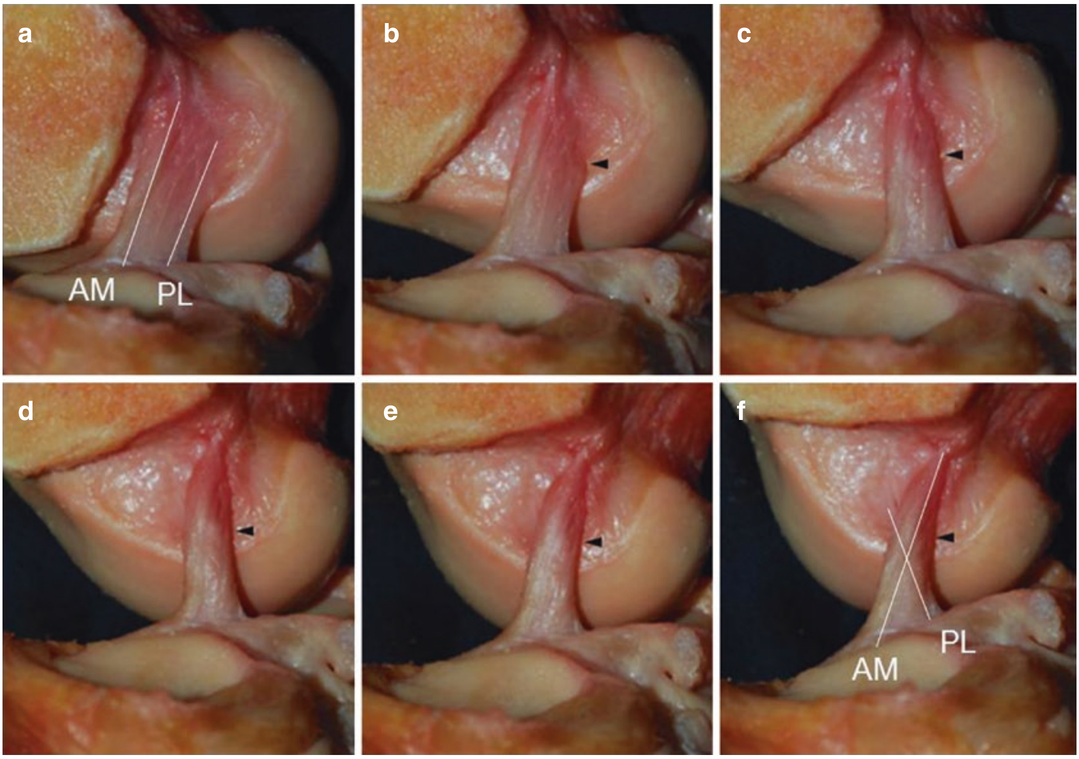

Fig. 16.1 Dynamic observation of the midsubstance and fanlike extension fibers during flexion-extension motion of the knee. At full extension (**a**), the midsubstance fibers had a paralel pattern. At 15–30° of flexion (**b**, **c**), the midsubstance fibers were found to slightly curve (*black arrowhead*) approximately at the postero-proximal edge of the direct attachment of the midsubstance fibers. At 45° (**d**), the curving of the ACL fibers was an obvious fold. At 60° (**e**), the midsubstance fibers started to become twisted, and the fold became deep specifically at the postero-distal portion. At 90° (**f**), the AM and PL bundles had a crossed pattern (From [32] with permission)

The ACL is attached to the posterior part of the medial surface of the lateral femoral condyle in the form of a segment of a circle with its anterior side straight and the posterior side convex [6, 15, 17, 18, 21–23]. The femoral footprint long axis is tilted forward 25° from the vertical, and its posterior convexity is parallel to the posterior articular border of the lateral femoral condyle. The ACL looks twisted because of the different direction of its femoral and tibial insertions [19]. On the tibia, the ACL is attached to a depressed area in front of and lateral to the medial intercondylar tubercle (anterior tibial spine). The tibial insertion of the ACL is wider and stronger than the femoral attachment [6].

The ACL is attached to the femur and tibia as a collection of individual fascicles that fan out over a broad flattened area [6, 24]. These fascicles have been divided into two groups according to their tibial insertion [6, 7, 16, 25]. The anteromedial (AM) bundle originates at the proximal aspect of the femoral attachment and inserts at the anteromedial aspect of the tibial insertion. The posterolateral (PL) bundle originates distally at the femoral origin of the ACL and inserts at the posterolateral aspect of the tibial footprint [6, 13, 16, 25, 26]. Both bundle attachments are larger in area than the cross section of the bundles at their midsubstances [15, 26].

The bundles of the ACL are not isometric through the range of motion (ROM). In extension, they are parallel, but as the knees flexes, the femoral origin of the PL bundle moves anteriorly, and the bundles cross [6, 7, 16] (Fig. 16.1).

16.3 Femoral Insertion

There are some controversies in the literature about the shape of the ACL femoral attachment. It has been reported as a segment of a circle with the anterior border almost straight and the posterior side convex [6, 17, 21] or an oval [5, 18, 19, 27] (Fig. 16.2).

The femoral insertion area of the ACL is smaller than the tibial insertion and it measures from 83 to 196 mm^2 [15, 21, 23, 28] (Table 16.1). Males have a greater femoral insertion area than females, and the insertion is smaller in right knees than in left knees [23].

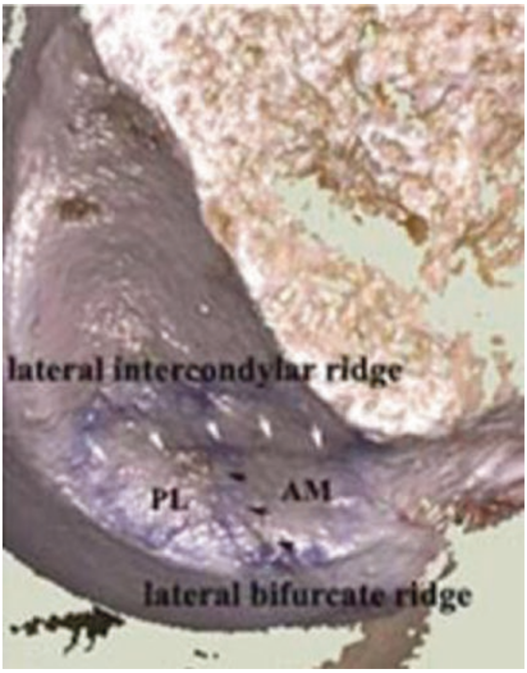

Fig. 16.2 View at the medial surface of the lateral condyle in 90° of flexion. The lateral intercondylar ridge is labeled with *white arrows*. Between the AM and the PL bundle runs the lateral bifurcate ridge (*black arrows*) [21] (From Kopf et al. [14])

Table 16.1 ACL femoral insertion area

References	Femoral area (mm^2)
Harner et al. [15]	113.0 ± 27
Ferretti et al. [21]	196.8 ± 23.1
Siebold et al. [23]	83.0 ± 19
Iwahashi et al. [28]	128.3 ± 10.5

The length and width of the ACL femoral attachment are 14.0–18.3 mm and 7.0–10.3 mm, respectively (Table 16.2) [18, 21, 23, 28–30]. The variation occurs due to different dissection and measurement methods used.

The femoral attachment of the AM bundle is greater than the PL one, corresponding to 52 % of the total insertion area of the femoral insertion of the ACL [23]. The area of insertion of the AM bundle varies from 44 to 120 mm^2, and the femoral footprint area of the PL bundle is from 40 to 76.8 mm^2 (Table 16.3) [15, 21, 23, 31].

The AM bundle attachment is concave with a radius of 25.7 ± 12 mm, while the PL bundle attachment is almost flat. This curvature of AM bundle attachment significantly increases its surface area [21]. The AM bundle extends to the posterior limit of the femoral notch, blending with the periosteum of the femoral shaft [29]. The length and width of the AM bundle femoral attachment are 7.2–11.3 mm and 4.7–7.5 mm, respectively. The length and width of the PL bundle femoral attachment are 6.0–11.0 mm and 4.7–7.6 mm, respectively (Table 16.4) [19, 23, 29, 31].

Table 16.2 ACL femoral insertion measurements

References	Length (mm)	Width (mm)
Colombet et al. [18]	18.3 ± 2.3	10.3 ± 2.7
Ferretti et al. [21]	17.2 ± 1.2	9.9 ± 0.8
Edwards et al. [29]	14.0 ± 2.0	7.0 ± 1.0
Siebold et al. [23]	15 ± 3.0	8.0 ± 2.0
Iwahashi et al. [28]	17.4 ± 0.9	8.0 ± 0.5
Kawaguchi et al. [30]	17.9 ± 2.0	8.5 ± 1.1

Table 16.3 AM and PL bundle femoral attachment area

	Area	
References	AM (mm^2)	PL (mm^2)
Harner et al. [15]	47 ± 13	49 ± 13
Takahashi et al. [31]	66.9 ± 2.3	66.4 ± 2.3
Ferretti et al. [21]	120 ± 19.8	76.8 ± 8.9
Siebold et al. [23]	44 ± 13	40 ± 11

Table 16.4 Measurements of the ACL AM and PL bundle femoral insertion

	AM		PL	
References	Length (mm)	Width (mm)	Length (mm)	Width (mm)
Mochizuki et al. [19]	9.2 ± 0.7	4.7 ± 0.6	6.0 ± 0.8	4.7 ± 0.6
Takahashi et al. [31]	11.3 ± 1.6	7.5 ± 1.3	11.0 ± 1.7	7.6 ± 1.0
Edwards et al. [29]	7.6 ± 1.5	7.0 ± 1.6	6.2 ± 2.3	5.5 ± 3.1
Siebold et al. [23]	7.2 ± 1.5	7.1 ± 1.5	7.0 ± 1.0	7.0 ± 2.0

16.3.1 Femoral Measurements

According to Harner et al. the femoral insertion of the ACL was 113 ± 27 mm^2. The femoral attachment area of the AM bundle was 47 ± 13 mm^2, and the correspondent area for the PL bundle was 49 ± 13 mm^2 [15].

Mochizuki et al. reported that the femoral attachment of the ACL was composed of two different shapes of fibers: one is the main attachment of the midsubstance of ACL fibers, and the other is the attachment of the thin fibrous tissue which extends from the midsubstance fibers and broadly spreads out like a fan on the posterior condyle [19, 32]. In their recent study [33], they found that during knee flexion, a fold in the ACL femoral attachment was observed at the border between the midsubstance and the fanlike extension fibers (Fig. 16.1), because the fanlike extension fibers were adhered to the bone surface, and the fiber location and orientation in relation to the femoral surface were constant, regardless of the knee flexion angle, while the orientation of the midsubstance fibers in relation to the femur changed during knee motion [33]. The attachment of the midsubstance fibers was significantly smaller than the attachment of the fanlike extension fibers [33]. The insertion of the midsubstance fibers involved cartilaginous zone, which is regarded as the direct insertion. On the other hand, the fanlike extension fibers directly attached onto the bone without forming transitional cartilaginous zone, which is regarded as the indirect insertion. Recently, Sasaki et al. [34] reported similar observations concerning the femoral attachment of the ACL.

Mochizuki et al. [19] could divide the ACL into AM and PL bundles. The length of the major axis of the AM and PL bundles, parallel to the posterior femoral cortex, averaged 9.2 ± 0.7 mm and 6.0 ± 0.8 mm, respectively. The length of the minor axis of both ACL bundles was 4.7 ± 0.6 mm. The distances from the attachment center of AM and PL bundles of the ACL to the posterior border of the lateral femoral condyle averaged 6.3 ± 0.6 mm and 8.6 ± 0.6 mm, respectively. The distances from the center of the AM and PL bundles to the anterior border of the lateral femoral condyle averaged 16.0 ± 1.5 mm and 5.8 ± 0.9 mm, respectively. When they used the “lateral wall clock” technique to describe the center of the AM and PL bundles of the ACL, the found the attachments at 01:40 and 03:10 position, respectively, for the left knee [19].

Ferretti et al. observed the femoral footprint length and width was 17.2 ± 1.2 mm and 9.9 ± 0.8 mm, respectively. The footprint area averaged 196.8 ± 23.1 mm^2. The areas of the AM and PL bundle attachments were 120 ± 19.8 mm^2 and 76.8 ± 8.9 mm^2, respectively [21].

Colombet et al. found that the proximodistal diameter of the ACL femoral attachment area was 18.3 ± 2.3 mm and its anteroposterior diameter was 10.3 ± 2.7 mm. The distance between the center of the AM bundle and the center of the PL bundle was 8.2 ± 1.2 mm. The distance between the posterior border of the ACL femoral attachment and the adjacent articular surface was 2.5 ± 1.1 mm [18].

According to Takahashi et al., the distance from the center of the AM and PL bundle femoral insertions to the posterior margin of the articular surface of the lateral condyle was 7.6 ± 1.5 mm and 7.0 ± 1.4 mm, respectively. The long axis of insertion of the AM and PL bundles was 11.3 ± 1.6 mm and 11.0 ± 1.7 mm, respectively. The short axis of insertion was 7.5 ± 1.3 mm for the AM bundle and 7.6 ± 1.0 mm for the PL. The footprint area of the

AM and PL bundles was 66.9 ± 2.3 mm^2 and 66.4 ± 2.3 mm^2, respectively [31].

They observed the lateral radiographs of the femoral condyles and found the center of the AM bundle to be, on average, 31.9 % from the posterior margin in the anteroposterior direction and 26.9 % from the roof in the proximal to distal direction, whereas that of the PL bundle was located, on average, at 39.8 % from the posterior margin and 53.2 % from the roof [31].

In the study of Edwards et al., the ACL attachment was 14.0 ± 2.0 mm long by 7.0 ± 1.0 mm wide. In all dissected pieces, the AM bundle extended to the posterior-proximal limit of the femoral notch, blending with the periosteum of the femoral shaft. The width of the AM bundle attachment was 7.6 ± 1.5 mm, and the center of the AM bundle was 4.3 ± 1.1 mm from the posterior edge of the notch, both measurements parallel to the femoral axis. The diameter of the AM bundle femoral insertion parallel to the femoral roof (Blumensaat's line) was 7.0 ± 1.6 mm, and the distance between the center of the AM bundle and the posterior outlet was 4.6 ± 1.2 mm [29].

The width of the PL bundle attachment was 6.2 ± 2.3 mm, and the center of the PL bundle was 8.9 ± 2.1 mm from the posterior edge of the notch, both measurements parallel to the femoral axis. The diameter of the PL bundle femoral insertion parallel to the femoral roof (Blumensaat's line) was 5.5 ± 3.1 mm, and the distance between the center of the AM bundle and the posterior outlet was 7.3 ± 1.8 mm [29].

According to Siebold et al., the femoral ACL insertion area was 83 ± 19 mm^2, with a mean width of 8 ± 2 mm and a mean length of 15 ± 3 mm. They found the mean insertion area in men was significantly larger (98 ± 22 mm^2) than in women (76 ± 13 mm^2). The mean femoral insertion area of the AM bundle was 44 ± 13 mm^2 (52 % of the femoral insertion), with a mean width and length of 7.2 ± 1.5 mm and 7.1 ± 1.5 mm, respectively. The mean femoral insertion area of the PL bundle was 40 ± 11 mm^2 (48 % of the femoral insertion), with a mean width and length of 7.0 ± 1.0 mm and 7.0 ± 2.0 mm, respectively. They found the mean femoral ACL insertion area of right knees was significantly smaller compared with left knees [23].

Kai et al. [35] pointed out that the AM bundle was not attached on a flat aspect of the femur but on a cylindrical surface of the femoral intercondylar notch around the proximal outlet. Therefore, they suggested that three-dimensional clock system is needed to measure the center of the femoral attachment of the AM midsubstance fibers. They showed that the averaged center of the direct attachment of the AM bundle midsubstance fibers was located on the cylindrical surface of the femoral intercondylar notch at 10:37 (or 01:23) o'clock orientation in the distal view and at 5.0 mm from the proximal outlet of the intercondylar notch in the lateral view [35].

Kawaguchi et al. found the length of the femoral ACL attachment was 17.9 ± 2.0 mm. The width of the femoral attachment of the anterior fanlike extension was 4.3 ± 0.9 mm, the width of the central direct attachment was 8.5 ± 1.1 mm, and the width of the posterior fanlike extension was 5.7 ± 1.6 mm [30].

Iwahashi et al. evaluated the position and area of direct insertion of the ACL and found that the footprint length was 17.4 ± 0.9 mm and its width was 8.0 ± 0.5 mm. The ACL insertion area was 128.3 ± 10.5 mm^2.

Recently Śmigielski et al. found that the midsubstance portion of the ACL has a ribbonlike structure from its femoral insertion, and the ligament fibers are in continuity with the posterior femoral cortex. They could find no clear separation into two bundles [10].

16.3.2 Osseous Landmarks

Hutchinson and Ash described a distinctive change in the slope of the femoral notch roof that occurs just anterior to the femoral attachment of the ACL. They named it as the "resident's ridge" [36]. A different osseous landmark also called resident's ridge was described by William Clancy Jr. (direct communication), and it is a thick ridge in the medial wall of the lateral femoral condyle that runs through the entire ACL footprint, reaching the articular cartilage, with no ACL attached anterior to this ridge.

Ferretti et al. performed a 3D assessment and arthroscopic study of the ACL femoral attachment. They studied the "resident's ridge" first described by Clancy. However, to avoid discordance, they called it the lateral intercondylar ridge [21] (Fig. 16.3).

Farrow D. et al. studied the morphology of the intercondylar femoral notch and found the lateral intercondylar ridge in 194 of the 200 specimens [37]. Tsukada et al. [38] observed a great degree of positional and dimensional variation in the lateral intercondylar ridge, specifically concerning the distal part and slightly differences between men and women. They found that although the proximal part of the lateral intercondylar ridge (LIR) almost corresponded to the anterior margin of the ACL attachment, the anterior margin of the ACL attachment was commonly located anterior to the middle and distal parts of the LIR, having the greatest margin-ridge distance averaged 4.2 mm [38].

There is another ridge or a change of slope of the lateral femoral condyle that separates the AM and PL bundle insertions. This ridge, described as lateral bifurcate ridge, supports the concept that the ACL has two bundles, each one with distinct attachments. This is an important landmark to guide knee surgeons during the anatomic reconstruction of the ACL [21].

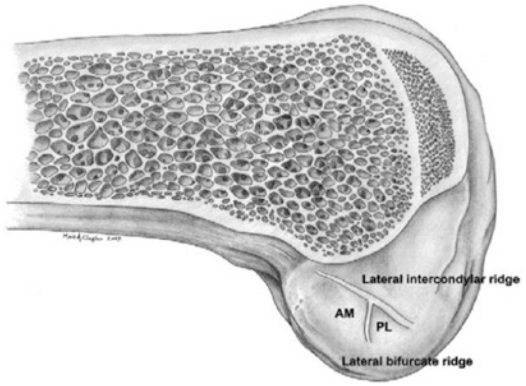

Fig. 16.3 The lateral wall of intercondylar notch. When the axis of the femur is parallel to the floor, the lateral bifurcate ridge runs anteroposterior, dividing the posterolateral and anteromedial femoral attachments, whereas the lateral intercondylar ridge runs proximodistal along the entire anterior cruciate ligament attachment [21]

To facilitate the understanding, the authors prefer to name lateral intercondylar ridge to describe the anterior limit of the ACL femoral insertion and the lateral bifurcate ridge referring to the slope modification between the AM and PL bundles.

16.4 Tibial Attachment

A wide variation of the shape and size of tibial ACL attachment has been described in the literature [14, 26], and it is known that the variation is related to the size of tibial plateau [26]. The tibial attachment has a more consistent size and appearance than those of the femoral insertion [18], and the femoral ACL insertion is smaller than the tibial one. Harner et al. described that the tibial attachment is 120 % of the femoral insertion area [15].

The tibial insertion area of the ACL is greater than the femoral attachment, 114–136 mm^2 (Table 16.5) [15, 39]. The ACL tibial attachment length measures 14.0–18.0 mm, except for the work of Girgis. The ACL tibial attachment width measures 9.0–12.7 mm (Table 16.6) [6, 18, 24, 26, 39–41].

The tibial attachment of the AM bundle is greater than the PL one. The ACL. The area of the tibial insertion of the AM bundle varies from 56 to 67 mm^2, and the tibial footprint area of the PL bundle is from 52 to 53 mm^2 (Table 16.7) [15, 31, 39] (Fig. 16.4).

Table 16.5 ACL tibial insertion area

References	Tibial area (mm^2)
Harner et al. [15]	136.0 ± 33
Siebold et al. [39]	114.0 ± 36

Table 16.6 ACL tibial insertion measurements

References	Length (mm)	Width (mm)
Girgis et al. [6]	30.0	–
Morgan et al. [24]	18.0	10.0
Cuomo et al. [40]	17.0 ± 2.0	9.0 ± 2.0
Colombet et al. [18]	17.6 ± 2.1	12.7 ± 2.8
Edwards et al. [26]	18.0 ± 2.0	9.0 ± 2.0
Siebold et al. [39]	14.0 ± 2.0	10.0 ± 2.0
Ferretti et al. [41]	18.1 ± 2.8	10.7 ± 1.9

16.4.1 Tibial Measurements

Girgis et al. found the average distance between the anterior border of the superior tibial articular surface and the anterior attachment of the ACL was 15 mm and the anteroposterior length of the ACL tibial attachment averaged 30 mm [6].

According to Edwards A. et al., the anteroposterior length of the ACL tibial attachment was 18 ± 2 mm (11–23) and the mediolateral width of the ACL tibial attachment was 9 ± 2 mm (7–14). Both measurements correlated to the size of the tibial plateau. The center of the ACL attachment was 35 ± 5 mm (26–57) anterior from the posterior tibial border, 15 ± 2 mm (11–18) anterior from the "over-the-back" ridge, and 5 ± 1 (3–7) mm lateral from the medial tibial spine border. They described the "over-the-back" ridge as a transverse interspinous ridge on the apex of the posterior slope of the tibial plateau, just anterior to the posterior cruciate ligament [26].

The center of the AM bundle was 17 ± 2 mm (13–19) anterior to the "over-the-back" ridge, 37 ± 3 mm (31–44) anterior from the posterior tibial axis, 12 ± 2 mm (7–17) posterior from the anterior tibial axis, and 5 ± 1 mm (3–8) lateral from the lateral border of the medial tibial spine [26].

Table 16.7 AM and PL bundle tibial attachment area

References	Area	
	AM (mm^2)	PL (mm^2)
Harner et al. [15]	56.0 ± 21.0	53.0 ± 21.0
Takahashi et al. [31]	67.0 ± 18.4	52.4 ± 17.6
Siebold et al. [39]	67.0 ± 31.0	52.0 ± 20.0

The center of the PL bundle was 10 ± 1 mm (8–13) anterior to the "over-the-back" ridge, 28 ± 3 mm (24–35) anterior from the posterior tibial axis, 21 ± 3 mm (13–26) posterior from the anterior tibial axis, and 4 ± 1 mm (3–5) lateral from the lateral border of the medial tibial spine [26].

The authors observed that the "over-the-back" ridge and the lateral face of the medial tibial spine could be useful to locate the center of ACL attachment and the center of AM and PL bundles [26].

Colombet et al. found that the anteroposterior diameter of the ACL tibial attachment area was 17.6 ± 2.1 mm and the mediolateral diameter of the ACL tibial attachment area was 12.7 ± 2.8 mm. They located the curved eminence that lay just anterior to the anterior extent of the tibial attachment of the posterior cruciate ligament and named as retroeminence ridge [18]. This landmark is described as the "over-the-back ridge" by other authors [26]. The distance between the center of the AM bundle and the retroeminence ridge was 17.5 ± 1.9 mm. The distance between the center of the AM and the PL bundle was 8.4 ± 0.6 mm. Consequently, the distance between the center of the PL and the retroeminence ridge was 9.1 mm, but this distance was not measured on this study. The distance between the anterior border of the ACL tibial attachment area and the anterior border of the tibial plateau was 13.1. ± 1.6 mm and

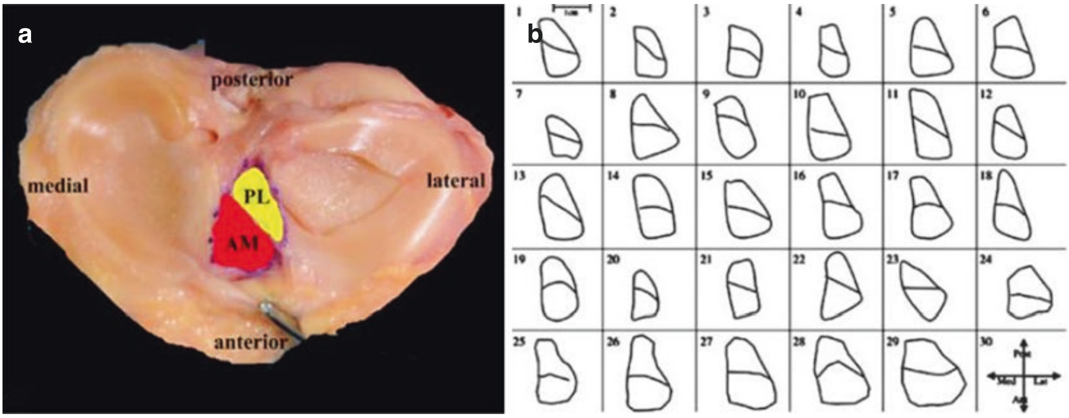

Fig. 16.4 Different tibial insertion pattern of ACL by: (**a**) oblique orientation, (**b**) the different findings by Edwards et al. [26]

between the posterior border of the ACL tibial attachment area and the posterior border of the tibial plateau was 24.9 ± 2.7 mm [18].

Morgan et al. found the anteroposterior diameter of the ACL tibial insertion averaged 18 mm (14–21). The mediolateral ACL tibial insertion averaged 10 mm (8–12). The sagittal distance between the center of the ACL tibial attachment and the anterior edge of the PCL averaged 7.1 mm (7–8) and it was independent of the knee size [24].

Siebold et al. found the average tibial insertion of the ACL was 114 ± 36 mm^2 (67–259). The average width of the ACL insertion was 10 ± 2 mm (7–15) and the average length of ACL footprint was 14 ± 2 mm (9–18). In their report, the average male tibial ACL insertion was larger than that of female knees, 130 ± 45 mm^2 and 106 ± 29 mm respectively. The ACL tibial insertion width was similar for both genders, but the length was smaller in female knees than in males, 14 ± 2 mm and 15 ± 2 mm, respectively [39].

The average tibial insertion area of the AM bundle was 67 ± 31 mm^2 (32–152) with an average width and length of 5 ± 1 mm (3–9) and 12 ± 2 mm (8–17), respectively. The average male tibial insertion area of the AM bundle was 72 ± 30 mm^2 versus 65 ± 31 mm^2 in female knees. The average width of the tibial insertion of the ACL AM bundle was similar for both genders and the average length was smaller in females knees (11 ± 2 mm) than in males (13 ± 2 mm) [39].

The insertion area of the PL bundle averaged 52 ± 20 mm^2 (22–90) with an average width and length of 4 ± 1 mm (2–7) and 10 ± 2 mm (7–14) respectively. The average male tibial PL bundle insertion area was bigger than that of the female knees, 55 ± 16 mm^2 and 51 ± 22 mm^2, respectively. The average width of the ACL PL bundle was 4 ± 1 mm, similar for both genders, and the average length of the ACL PL bundle was smaller in females than in male knees, 10 ± 1 mm and 11 ± 1 mm, respectively [39].

The tibial insertion area of the AM bundle was 12 % larger than that of PL bundle. The center if the AM bundle was 1 ± 2 mm anterior and 4 ± 1 mm medial to the center of PL bundle. The distance between both centers of the bundles was 5 mm [39].

According to Harner et al., the tibial insertion of the ACL was 136 ± 33 mm^2. The tibial attachment area of the AM bundle was 56 ± 21 mm^2 and the correspondent area for the PL bundle was 53 ± 21 mm^2 [15].

Cuomo et al. used 21 fresh-frozen knee cadaver specimens and found the anterior and posterior limits of the ACL tibial attachment at 22 ± 3 mm (16–27) and 6 ± 2 mm (2–8) from the over-the-back position, respectively. The tibial attachment was on averaged 17 ± 2 mm (12–19) long and 9 ± 2 mm (7–16) wide [40].

Takahashi et al. examined 31 tibial plateaus of cadaver knees (32 femur and 31 tibia) and found that the distance from a line between the anterior margin of the articular cartilage of the medial and lateral tibial condyles to the centers of the AM and PL bundle was 13.0 ± 2.3 and 14.7 ± 2.8 mm, respectively. On the sagittal plane, the AM bundle was 28.6 ± 5.3 % from the anterior limit of the tibial plateau and the PL bundle was 32.1 ± 5.9 %. Mediolaterally, the AM and the PL bundle was 44.2 ± 2.4 % and 52.4 ± 2.2 % respectively from the medial border of the tibial plateau. The tibial attachment area of the AM bundle was 67.0 ± 18.4 mm^2, whereas that of the PL bundle was 52.4 ± 17.6 mm^2 [31].

Ferretti et al. found that only the anterior root of lateral meniscus may not be always used as a landmark for tibial tunnel drilling; the authors suggested also to use bony landmarks as the medial tibial spine. They studied eight cadaveric knees and found the length and width of the ACL tibial insertion were 18.1 ± 2.8 mm and 10.7 ± 1.9 mm, respectively. The width of the AM bundle was 11.1 ± 2.1 mm and the PL bundle was 7.9 ± 2.0 mm. The ACL center was 9.1 ± 1.5 mm posterior to the intermeniscal ligament and 5.7 ± 1.1 mm anterior to a projected line from the apex of the medial tibial eminence. The center of the AM bundle was at 4.6 ± 0.7 mm posterior to the intermeniscal ligament. The center of the PL bundle was 1.4 ± 0.7 mm anterior to the medial tibial eminence [41].

Hara et al. [32] first reported that, in histological evaluation of the tibial attachment, there was no fibrous insertion in the center of the posterior portion of the ACL tibial attachment. The small bundles of the distal portion of the posterolateral bundle on the femur were found separately attached to the medial and lateral portions of the tibial attachment. In the bare area, there were fat tissue and vascular bundles [32]. Recently, Siebold et al. described the tibial insertion of the ACL has a "C" shape from along the medial tibial spine to the anterior aspect of the anterior root of the lateral meniscus with a mean width of 12.6 mm and thickness of 3.3 mm. They observed that there are no central fibers on the ACL tibial footprint and no PL insertion. They affirmed that the posterior fibers of the "C" are inserting medially along the medial spine, and these fibers were named posteromedial fibers. According to the authors, there is a structure like a belt over the tibial plateau, including the anterior horn of the lateral meniscus, the "C"-shaped insertion of the ACL, and the posterior horn of the lateral meniscus. These elements, together, form a "raindrop-like ring structure." Macroscopically, they divided the tibial insertion of the ACL into two parts. The direct one, which corresponds to the "C"-shaped midsubstance insertion, and the indirect part, which is the anterior and broader attachment of the "fanlike" extension. The direct and indirect insertions together were form a "duck-foot-like" footprint [42].

16.5 Biomechanical of the Anteromedial and Posterolateral Bundles

It is well established that the AM and PL bundles of the ACL have different strains during the range of motion of the knee.

According to Kurosawa et al. [11], the AM bundle is stretched in the full extension position, relaxed at 20–60° of knee flexion and again stretched in a flexion position of more than 90°. The PL bundle is stretched in the full extension position, whereas it becomes slack in a flexion position, in response to an anterior tibial load [11].

Sakane et al. showed that the magnitude of the force in the PL bundle in response to anterior tibial loading was greater than that in the AM bundle, especially when the knee was near extension. Changes in the PL bundle during knee flexion-extension revealed trends similar to those for the whole ACL. Moreover, the forces in the AM bundle remained relatively constant during, being unaffected by changes in flexion angle and only minimally affected by changes in applied anterior tibial load [43].

Gabriel et al. [44] described that, under a combined rotatory load, the PL bundle is as important as the AM bundle, especially when the knee is in the near extension position.

Recently, Zantop et al. [13] showed that isolated resection of the PL bundle significantly increases anterior tibial translation at 30° of knee flexion and combined rotation at 0° and 30°, as compared with the intact knee and isolated resection of the AM bundle. That is, rupture of the ACL increases both anterior translation and internal rotation, resulting in a large movement of the mobile lateral tibial plateau.

Mochizuki et al. [33] reported that, during knee flexion, a deep fold in the ACL femoral attachment was observed at the border between the midsubstance and the fanlike extension fibers. This observation suggested that the fanlike extension fibers may have a limited role in resisting tibial displacement. Based on Mochizuki's study, Kawaguchi et al. [30] conducted a sequential cutting study of the femoral attachment of the ACL, when tibial anteroposterior 6-mm translations were applied at 0–90° of knee flexion. The midsubstance fiber attachment area resisted 82–90 % of the anterior drawer force, while the posterior fanlike extension fiber attachment area resisted 11–15 %. These results showed that the fanlike extension fibers contributed very little. They suggests that, in ACL reconstruction, the most important area on the femur, in terms of resisting displacement of the tibia, was in the central anterior part of the femoral ACL attachment, near the roof of the intercondylar notch [30].

Kato et al. studied the biomechanics of the human triple-bundle ACL. They showed that the intermediate (IM) bundle can be divided from the AM and PL bundle not anatomically but functionally. The AM bundle stabilizes the knee against both anterior and rotatory loads, that the PL bundle stabilizes the knee specially near full extension, and that IM bundle plays a supplemental role to the AM and PL bundles through all flexion angles, especially from 30 to 45°, against rotatory load [45].

16.6 The Triple Bundle Concept

In many mammals, a triple-bundle structure of the ACL is clearly discernible [46, 47]. Norwood et al. [8] first reported that the ACL can be divided into three bundles [anteromedial (AM), intermediate (IM), and posterolateral (PL)] [8]. Moreover, Amis and Dawkins [7] reported that the ACL can be divided into three bundles using cadaveric knees to show the changes in the length of each ACL fiber bundle.

Otsubo et al. [9] were able to identify the three ACL bundles in all knees dissected. At 0° and 30° of knee flexion, the three bundles ran parallel to each other. At 90° and 120°, the IM bundle became anterior and ran more vertically than the AM bundle. In addition, the PL bundle was arranged vertically relative to the AM and IM bundles. The bundles had a tendency to twist around each other as knee flexion increased (Fig. 16.5).

The PL bundle occupied the distal-posterior half of the femoral insertion area, whereas the AM and IM bundles were attached to the proximal anterior half (Fig. 16.6). The IM bundle attachment was located anterior and inferior to the area of the AM bundle. On the tibia, the AM, IM, and PL bundles were attached to the anteromedial, anterolateral, and posterolateral portions

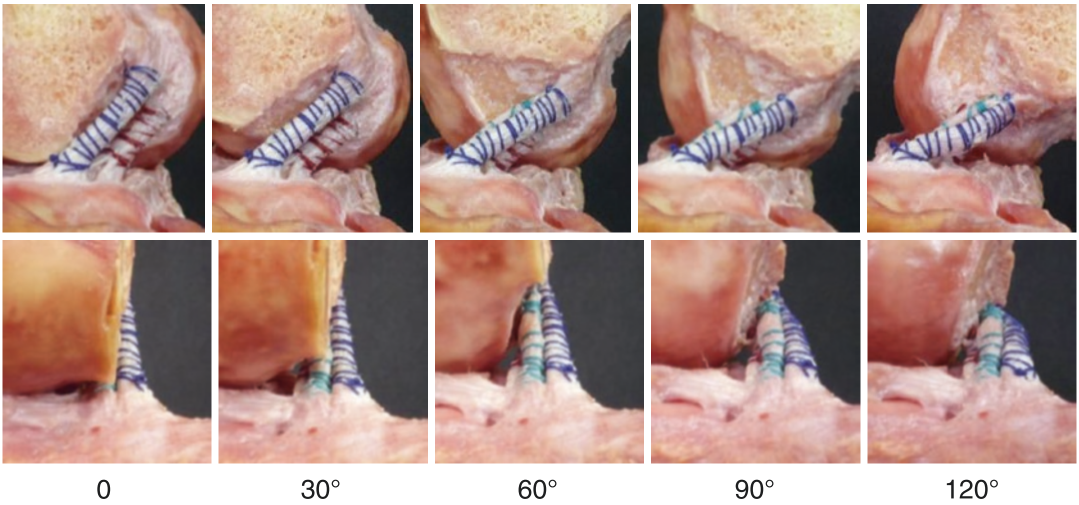

Fig. 16.5 Sagittal and frontal views of three separated ACL bundles. A different-colored thread was wound around each fiber bundle. *Blue*, *green,* and *red threads* indicate anteromedial, intermediate, and posterolateral bundles, respectively [9]

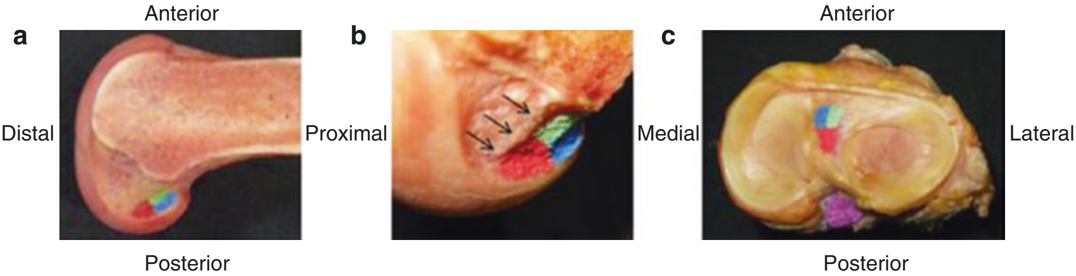

Fig. 16.6 Attachment areas of anteromedial (*blue*), intermediate (*green*), and posterolateral (*red*) ACL bundles. (**a**) Femur sagittal view from the medial side. (**b**) Femur oblique view from the anteromedial side (*arrow*: Resident's ridge). (**c**) Tibia axial view from the proximal side

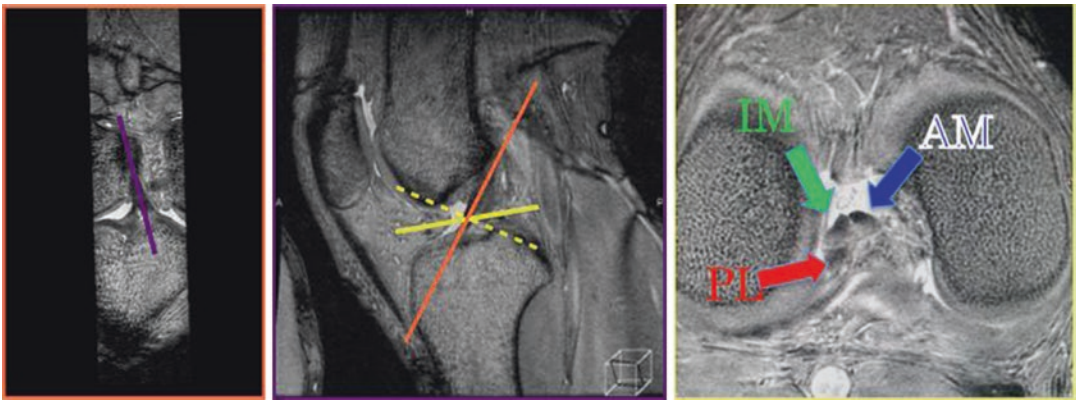

Fig. 16.7 A 36-year-old man was examined using 3D isotropic sagittal MRI with the sequence of Coherent Oscillatory State acquisition for the Manipulation of Image Contrast (COSMIC) with fat suppression. The viewing plane was decided to maximally visualize the three bundles. ACL bundle anatomy was best depicted in the ACL axial plane at the center of the ACL in all knees [9]

of the attachment area, respectively, forming a triangle [9] (Fig. 16.6).

The average area of the femoral attachment was 124.6 mm^2 (117.5–130.3 mm^2). The proportions of the AM, IM, and PL bundles were 29 %, 28 %, and 43 %, respectively. The average area of the tibial attachment was 119.1 mm^2, with the proportions of 29 %, 26 %, and 45 % for the AM, IM, and PL bundles, respectively [9].

The three bundles in the native ACL were visually distinguished with 3D-COSMIC isotropic imaging of 3-T magnetic resonance imaging (MRI) (Fig. 16.7) [9].

The ACL could to be macroscopically divided into AM and PL bundles at 90° flexion of the knee. When the “anteromedial” bundle was observed from the front, the existence of a septum between the medial and lateral fibers was confirmed around the tibial attachment. This septum allowed the authors to divide the “anteromedial” bundle into the medial AM and lateral IM bundles. The septum was not clearly recognized. However, by loading the anterior tibial drawer at a 90° flexion of the knee, the septum became evident. This may suggest a difference in the biomechanical roles of the two bundles during the anterior translation of the tibia [9].

In response to 100 N of the anterior force, the AM and PL bundle forces were slightly higher than the IM bundle force at full extension. The AM bundle force remained at a high level up to 90° of flexion, with significant differences compared with the IM bundle forces at 15°, 30°, and 60° of flexion and the PL bundle force at 90° of flexion [9]. The AM bundle is the primary stabilizer to the tibial anterior drawer through a wide range of motion, whereas the IM bundle is the secondary stabilizer in deep flexion angles. The PL bundle is the crucial stabilizer to hyperextension as well as tibial anterior drawer at full extension.

References

1. Shen W, Jordan S, Fu F (2007) Review article: anatomic double bundle anterior cruciate ligament reconstruction. J Orthop Surg 15:216–221
2. Kongtharvonskul J, Attia J, Thamakaison S et al (2013) Clinical outcomes of double- vs single-bundle anterior cruciate ligament reconstruction: a systematic review of randomized control trials. Scand J Med Sci Sports 23:1–14. doi:10.1111/j.1600-0838.2011.01439.x
3. Suomalainen P, Kannus P, Järvelä T (2013) Double-bundle anterior cruciate ligament reconstruction: a review of literature. Int Orthop 37:227–232. doi:10.1007/s00264-012-1680-9
4. Mascarenhas R, Cvetanovich GL, Sayegh ET et al (2015) Does double-bundle anterior cruciate ligament reconstruction improve postoperative knee stability compared with single-bundle techniques? A systematic review of overlapping meta-analyses. Arthroscopy 31:1185–1196. doi:10.1016/j.arthro.2014.11.014
5. Odensten M, Gillquist J (1985) Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. J Bone Joint Surg 67:257–262

6. Girgis FG, Marshall JL, Monajem A (1975) The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res 106:216–231, 1126079
7. Amis A, Dawkins G (1991) Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg Br 73:260–267
8. Norwood LA, Cross MJ (1979) Anterior cruciate ligament: functional anatomy of its bundles in rotatory instabilities. Am J Sports Med 7:23–26
9. Otsubo H, Shino K, Suzuki D et al (2012) The arrangement and the attachment areas of three ACL bundles. Knee Surg Sports Traumatol Arthrosc 20:127–134. doi:10.1007/s00167-011-1576-z
10. Smigielski R, Zdanowicz U, Drwiega M et al (2014) Ribbon like appearance of the midsubstance fibres of the anterior cruciate ligament close to its femoral insertion site: a cadaveric study including 111 knees. doi:10.1007/s00167-014-3146-7
11. Kurosawa H, Yamakoshi K, Yasuda K, Sasaki T (1991) Simultaneous measurement of changes in length of the cruciate ligaments during knee motion. Clin Orthop Relat Res 265:233–240
12. Bach JM, Hull ML, Patterson HA (1997) Direct measurement of strain in the posterolateral bundle of the anterior cruciate ligament. J Biomech 30:281–283
13. Zantop T, Herbort M, Raschke MJ et al (2007) The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. Am J Sports Med 35:223–227. doi:10.1177/0363546506294571
14. Kopf S, Musahl V, Tashman S et al (2009) A systematic review of the femoral origin and tibial insertion morphology of the ACL. Knee Surg Sports Traumatol Arthrosc 17:213–219. doi:10.1007/s00167-008-0709-5
15. Harner CD, Baek GH, Vogrin TM et al (1999) Quantitative analysis of human cruciate ligament insertions. Arthroscopy 15:741–749. doi:10.1016/S0749-8063(99)70006-X
16. Chhabra A, Starman JS, Ferretti M et al (2006) Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. J Bone Joint Surg 88:2–10. doi:10.2106/JBJS.F.00616
17. Arnoczky SP (1983) Anatomy of the anterior cruciate ligament. Clin Orthop Relat Res 172:19–25
18. Colombet P, Robinson J, Christel P et al (2006) Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. Arthroscopy 22:984–992. doi:10.1016/j.arthro.2006.04.102
19. Mochizuki T, Muneta T, Nagase T et al (2006) Cadaveric knee observation study for describing anatomic femoral tunnel placement for two-bundle anterior cruciate ligament reconstruction. Arthroscopy 22:356–361. doi:10.1016/j.arthro.2005.09.020
20. Triantafyllidi E, Paschos NK, Goussia A et al (2013) The shape and the thickness of the anterior cruciate ligament along its length in relation to the posterior cruciate ligament: a cadaveric study. Arthroscopy 29:1963–1973. doi:10.1016/j.arthro.2013.09.007
21. Ferretti M, Ekdahl M, Shen W, Fu FH (2007) Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy 23:1218–1225. doi:10.1016/j.arthro.2007.09.008
22. Duthon VB, Barea C, Abrassart S et al (2006) Anatomy of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 14:204–213. doi:10.1007/s00167-005-0679-9
23. Siebold R, Ellert T, Metz S, Metz J (2008) Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement-a cadaver study. Arthroscopy 24:585–592. doi:10.1016/j.arthro.2007.12.008
24. Morgan CD, Kalman VR, Grawl DM (1995) Definitive landmarks for reproducible tibial tunnel placement in anterior cruciate ligament reconstruction. Arthroscopy 11:275–288. doi:10.1016/0749-8063(95)90003-9
25. Petersen W, Zantop T (2007) Anatomy of the anterior cruciate ligament with regard to its two bundles. Clin Orthop Relat Res 454:35–47. doi:10.1097/BLO.0b013e31802b4a59
26. Edwards A, Bull AMJ, Amis AA (2007) The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament Part 1: tibial attachment. Knee Surg Sports Traumatol Arthrosc 15:1414–1421. doi:10.1007/s00167-007-0417-6
27. Luites JWH, Wymenga AB, Blankevoort L, Kooloos JGM (2007) Description of the attachment geometry of the anteromedial and posterolateral bundles of the ACL from arthroscopic perspective for anatomical tunnel placement. Knee Surg Sports Traumatol Arthrosc 15:1422–1431. doi:10.1007/s00167-007-0402-0
28. Iwahashi T, Shino K, Nakata K et al (2010) Direct anterior cruciate ligament insertion to the femur assessed by histology and 3-dimensional volume-rendered computed tomography. Arthroscopy 26:S13–S20. doi:10.1016/j.arthro.2010.01.023
29. Edwards A, Bull AM, Amis AA (2008) The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament Part 2: femoral attachment. Knee Surg Sports Traumatol Arthrosc 16:29–36. doi:10.1007/s00167-007-0410-0
30. Kawaguchi Y, Kondo E, Takeda R et al (2015) The role of fibers in the femoral attachment of the anterior cruciate ligament in resisting tibial displacement. Arthroscopy 31:435–444. doi:10.1016/j.arthro.2014.08.033
31. Takahashi M, Doi M, Abe M et al (2006) Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. Am J Sports Med 34:787–792. doi:10.1177/0363546505282625
32. Hara K, Mochizuki T, Sekiya I et al (2009) Anatomy of normal human anterior cruciate ligament attachments evaluated by divided small bundles. Am J Sports Med 37:2386–2391. doi:10.1177/0363546509340404
33. Mochizuki T, Fujishiro H, Nimura A et al (2014) Anatomic and histologic analysis of the mid-substance

and fan-like extension fibres of the anterior cruciate ligament during knee motion, with special reference to the femoral attachment. Knee Surg Sports Traumatol Arthrosc 22:336–344. doi:10.1007/s00167-013-2404-4

34. Sasaki N, Ishibashi Y, Tsuda E et al (2012) The femoral insertion of the anterior cruciate ligament: discrepancy between macroscopic and histological observations. Arthrosc – J Arthrosc Relat Surg 28:1135–1146. doi:10.1016/j.arthro.2011.12.021
35. Kai S, Kondo E, Kitamura N et al (2013) A quantitative technique to create a femoral tunnel at the averaged center of the anteromedial bundle attachment in anatomic double-bundle anterior cruciate ligament reconstruction. BMC Musculoskelet Disord 14:189. doi:10.1186/1471-2474-14-189
36. Hutchinson MR, Ash SA (2003) Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthroscopy 19:931–935. doi:10.1016/j.arthro.2003.09.002
37. Farrow LD, Chen MR, Cooperman DR et al (2007) Morphology of the femoral intercondylar notch. J Bone Joint Surg 89:2150–2155. doi:10.2106/JBJS.F.01191
38. Tsukada S, Fujishiro H, Watanabe K et al (2014) Anatomic variations of the lateral intercondylar ridge: relationship to the anterior margin of the anterior cruciate ligament. Am J Sports Med 42:1110–1117. doi:10.1177/0363546514524527
39. Siebold R, Ellert T, Metz S, Metz J (2008) Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. Arthroscopy 24:154–161. doi:10.1016/j.arthro.2007.08.006
40. Cuomo P, Edwards A, Giron F et al (2006) Validation of the 65° Howell guide for anterior cruciate ligament reconstruction. Arthroscopy 22:70–75. doi:10.1016/j.arthro.2005.10.016
41. Ferretti M, Doca D, Ingham SM et al (2012) Bony and soft tissue landmarks of the ACL tibial insertion site: an anatomical study. Knee Surg Sports Traumatol Arthrosc 20:62–68. doi:10.1007/s00167-011-1592-z
42. Siebold R, Schuhmacher P, Fernandez F et al (2014) Flat midsubstance of the anterior cruciate ligament with tibial "C"-shaped insertion site. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3058-6
43. Sakane M, Fox RJ, Woo SL-Y et al (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 15:285–293. doi:10.1002/jor.1100150219
44. Gabriel MT, Wong EK, Woo SLY et al (2004) Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. J Orthop Res 22:85–89. doi:10.1016/S0736-0266(03)00133-5
45. Kato Y, Ingham SJM, Maeyama A et al (2012) Biomechanics of the human triple-bundle anterior cruciate ligament. Arthroscopy 28:247–254. doi:10.1016/j.arthro.2011.07.019
46. Tantisricharoenkul G, Linde-Rosen M, Araujo P et al (2014) Anterior cruciate ligament: an anatomical exploration in humans and in a selection of animal species. Knee Surg Sports Traumatol Arthrosc 22:961–971. doi:10.1007/s00167-013-2463-6
47. Kato Y, Ingham SJM, Linde-Rosen M et al (2010) Biomechanics of the porcine triple bundle anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 18:20–25. doi:10.1007/s00167-009-0893-y

Anatomy of the ACL Insertions: Arthroscopic Identification of the Attachments

17

Jorge Chahla and Robert F. LaPrade

17.1 Relevant Femoral Bony Landmarks

Bony landmarks on the lateral femoral condyle, including the lateral intercondylar ridge (LIR), bifurcate ridge (BR), femoral notch roof, over-the-top position (OTP), and the posterior notch outlet, have been described as consistent landmarks for determining anteromedial (AM) and posterolateral (PL) ACL bundle tunnel placement [1]. For the purpose of description of the landmarks, proximal/distal will be considered cephalic/caudal respectively and anterior/posterior will be ventral/dorsal respectively.

Identification of the LIR and BR has been reported to be an accurate and reliable method to locate the native ACL femoral insertion site [2] (Fig. 17.1). The LIR (commonly known as the "resident's ridge" as described by Clancy [3]) is particularly useful because it serves as the anterior margin of both the individual bundles and the overall ACL femoral attachment. It has shown to be consistent in all specimens in cadaveric and arthroscopic studies [1, 4–6]. Moreover, the LIR is usually identifiable arthroscopically, whereas the BR, which separates the AM and PL bundle femoral attachments, is more subtle, difficult to locate, and may not always be apparent during arthroscopic surgery [1]. Of note, the BR represents a delicate change of slope resembling a ledge rather than a convex ridge. Identification of the BR may be difficult arthroscopically, especially when using motorized shavers or curettes to clean off the lateral femoral wall. When the BR is visible and palpable, it has the potential to serve as a useful surgical landmark, especially for single- and double-bundle ACL reconstructions.

Landmarks from the distal and posterior articular cartilage margins, the proximal point, and the posterior point can also serve as references to guide ACL femoral reconstruction tunnel placement [1]. In particular, the perpendicular intersection of a line extending proximally from the distal articular cartilage margin and a line extending anteriorly from the posterior articular cartilage margin may be useful for locating the center of the ACL attachment [1]. For the reasons mentioned above, a patient's native anatomy should be carefully preserved by dissection (with mechanized shavers or thermal devices) of the anatomical insertions in order to leave more intact landmarks to guide tunnel placement.

17.2 Femoral Footprint Morphology and Location

The femoral insertion site of the ACL is described as either circular or oval shaped and similar in size between the two bundles (AM and PL). The areas of the entire ACL insertions are 113 ± 27 mm^2 and 136 ± 33 mm^2 for the femur and tibia, respec-

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DOI 10.1007/978-3-662-52742-9_17

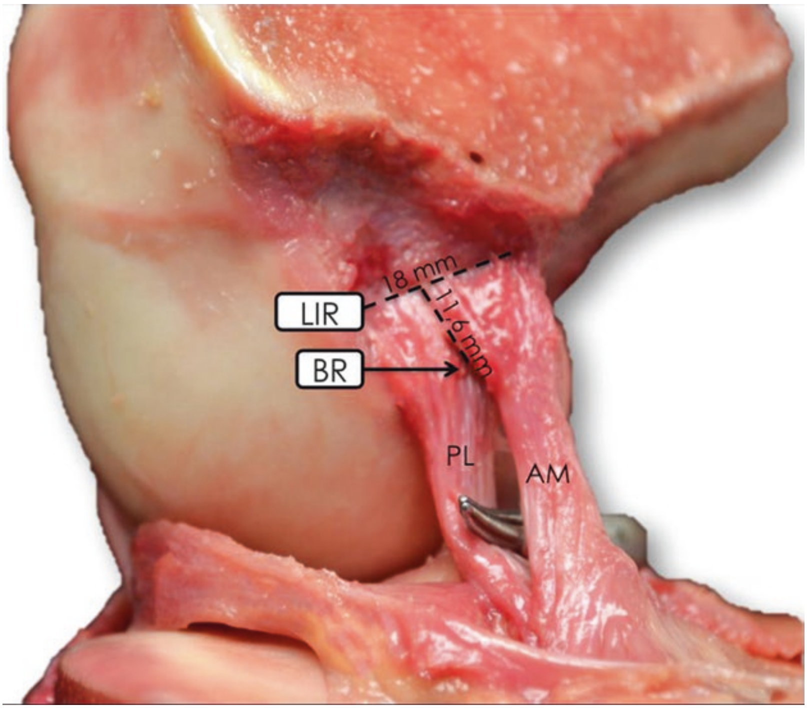


Fig. 17.1 Lateral view of a hemi-sectioned right knee illustrating relevant femoral bony landmarks. The lateral intercondylar ridge (*LIR*) represents the most anterior femoral attachment for both bundles (18 mm average length) and the subtler bifurcate ridge (*BR*), which extends from the LIR to the posterior cartilage (11.6 mm average length)

tively [7]. Hensler et al. [8] reported that only 61 % of the femoral insertion is reconstructed with standard tunnel reaming. The overall ACL attachment center is 6.1 mm posterior to the lateral intercondylar ridge, 1.7 mm proximal to the bifurcate ridge, 14.7 mm proximal to the distal cartilage margin, and 8.5 mm anterior to the posterior cartilage margin [1]. The footprint of the AM bundle is approximately 52 % of the total femoral ACL insertion area, and that of the PL bundle is approximately 48 % [9]. The AM bundle femoral attachment center is 7.1 mm posterior to the lateral intercondylar ridge, 4.8 mm proximal to the bifurcate ridge, 18.6 mm proximal to the distal cartilage margin, and 11.7 mm anterodistal to the proximal point. The PL bundle attachment center is 3.6 mm posterior to the LIR, 5.2 mm distal to the bifurcate ridge, 10.7 mm proximal to the distal cartilage margin, and 5.7 mm anterior to the posterior cartilage margin [1]. Slight ACL size variations may exist depending on the age, gender, or size of the specimen under study.

The AM and PL bundle attachments appear differently as the knee flexion angle changes (Fig. 17.2). Therefore, the knee flexion angle has been assumed to be the most powerful and modifiable factor influencing the arthroscopic view [10].

17.3 Relevant Tibial Bony and Soft Tissue Landmarks

Specific bony landmarks assessed for the ACL tibial attachment include the lateral and medial tibial eminences, the medial and lateral tibial plateau articular cartilage borders, the ACL ridge, the ACL tubercle, the anterolateral fossa, and the retroeminence ridge [1]. Relevant soft tissue landmarks are the anterior horn of the lateral meniscus and the anterior intermeniscal ligament (AIL).

The *anterolateral fossa* is a bony depression immediately medial to the lateral tibial plateau articular cartilage border and anterior to the lateral tibial eminence, which corresponds to the attachment of the anterior horn of the lateral meniscus. The *ACL ridge* is an anterior bony elevation that courses between the anterolateral fossa and the medial tibial plateau articular cartilage border. The *ACL tubercle* defines the lateral-most aspect of the ACL ridge. The ACL ridge and tubercle serves as a landmark for the anterior-most border of the ACL tibial attachment. The retroeminence ridge (“over-the-back” ridge) is a transverse ridge located at the apex of the posterior slope of the tibial plateau in close relationship with the anterosuperior aspect of the PCL tibial attachment [1].

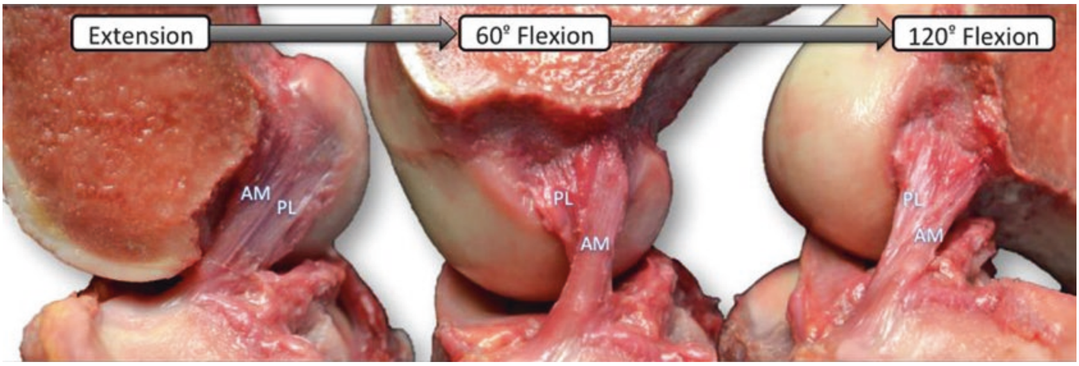


Fig. 17.2 Lateral view of a hemi-sectioned right knee demonstrating changes in bundles and femoral insertion sites with progressive knee flexion (extension, 60° of flexion and 120° flexion). This relationship is essential to understand for the arthroscopist in order to perform an anatomical reconstruction

17.4 Tibial Footprint Morphology and Location

Harner et al. [7] reported that the tibial insertion of the ACL is 120 % of the area of the femoral insertion site. Kopf et al. [11] showed that with standard drilling, only 57 % of the native tibial insertion is reproduced. The tibial insertion site of the ACL has been described as having a duck-foot shape [5]. The division between the attachments of the AM and PL bundles on the tibia is obliquely oriented and courses in a posteromedial-to-anterolateral direction, with an average distance between the bundle centers of 10.1 mm. The distinctive contour of this division imparts a convex, comma-shaped appearance to the AM bundle footprint, enveloping the medial convex contour of the PL bundle [1]. The ACL center is 10.5 mm posterior to the ACL ridge, 13 mm anterior to the retroeminence ridge, and 7.5 mm medial (and slightly anterior [7]) to the anterior horn of the lateral meniscus [1] (Figs. 17.3 and 17.4).

Fibrous connections extending from the anterior horn of the lateral meniscus attachment to the ACL bundles are constant (the anterior aspect of the anterior horn of the lateral meniscus attachment is aligned with the AM bundle, whereas the posterior aspect fibrous attachments are aligned with the PL bundle) [1] (Fig. 17.5).

In regard to the tibial eminences, no ACL insertion is located posterior to the lateral tibial eminence [7]. The medial tibial eminence has less variability, having a constant relationship with the center of the ACL and its bundles [7]. Harner [7] reported the AIL as a reliable landmark (center of

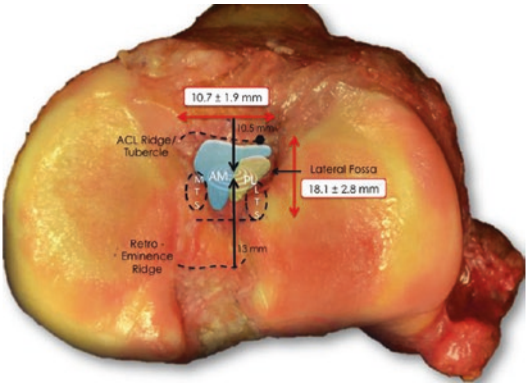


Fig. 17.3 Superior view of a right tibia depicting distances between the most reliable tibial bony landmarks. The average distance of the tibial footprint is indicated with their respective standard deviations. An important anatomic fact is that none of the ACL tibial insertion is posterior to the lateral eminence

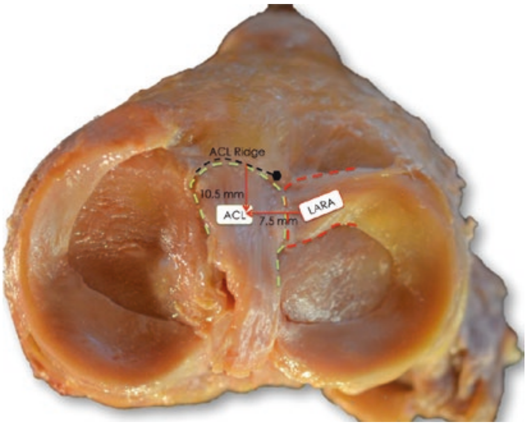


Fig. 17.4 Superior (axial) view of a right tibia showing the relationship between the lateral meniscus anterior root attachment (*LARA*) and the ACL

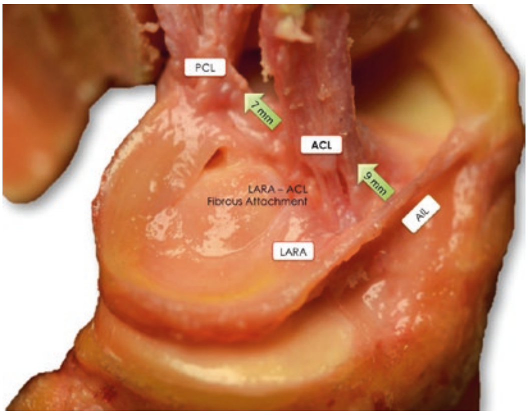


Fig. 17.5 Superolateral view of a right tibia demonstrating the most widely used soft tissue landmarks. From anterior to posterior, the relationship between soft tissue landmarks is illustrated. Note the fibrous tissue connecting the anterolateral root (*LARA*) to the ACL

the tibial ACL attachment is 9.1 ± 1.5 mm posterior to the posterior edge of the AIL) [7]. However, a recent study by Kongcharoensombat [12] reported that the AIL coincides with the anterior edge of the ACL tibial footprint in the sagittal plane.

The posterior cruciate ligament (PCL) has historically been used as a landmark (ACL tibial attachment is approximately 7 mm anterior) [7, 13]. However, the utility of this landmark depends on which aspect of the PCL is used as a reference, if the PCL is injured, and whether the tibia is anteriorly subluxed on the femur. It is now recognized that tibial tunnel positioning based on the PCL is located too posterior to the native ACL tibial attachment. Thus, the anterior root of the lateral meniscus and the retroeminence ridge are more reliable landmarks for referencing the ACL tibial attachment site [1].

17.5 Positioning and Essential Arthroscopic Landmarks

Several cadaveric and clinical studies have assessed ACL tunnel positioning [14–17]. However, 10–40 % of tunnel placements in ACL reconstructions are reportedly malpositioned [10], comprising the main reason (52 %) for ACL revision surgery [18]. The high rate of tunnel misplacement can be attributed to the position of the portals, the degree of flexion during identification of the footprints, anatomical variation [10], or arthroscopic image distortion [19, 20]. Hoshino [19] reported that the knee should be positioned at 90° when determining graft placement because the accuracy of the footprint placement could be reproduced more accurately than in a hyperflexion state. Moreover, there was a tendency of distal misplacement of the tunnels with the knee at 110° [10]. Conversely, surgeons can identify osseous landmarks more easily with a more flexed position (110–120°) as the lateral femoral condyle acquires a lower and shallower position in the arthroscopic view [19, 21]. Some surgeons prefer a more flexed position [22, 23] because that has less risk of blowing out the posterior wall of the lateral femoral condyle, making a tunnel with insufficient length or damage to the lateral structures [24]. Therefore, we recommend 90° of knee flexion to choose tunnel position and flexion of 110° or more for improved consistency in tunnel creation in order to prevent cortex fracture and also to maximize tunnel length.

Another risk factor for tunnel malpositioning is the image distortion since peripheral regions may be altered, especially when viewing angle is not straight [19]. Therefore, when reaming the femoral tunnel, initial visualization through the anteromedial portal is preferred [19, 21].

The most accurate anatomic landmark for arthroscopic ACL reconstruction is the native ACL remnant [6, 9, 25]. However, in a chronic setting or in a revision surgery, this may not be visible [9]. Therefore, for the femoral tunnels, the OTP and the LIR remain the most reliable osseous landmarks and are the senior author's (RFL) preferred method. For this purpose, a 7 mm offset guide can be utilized to place the tunnel anterior to the posterior margin of the femoral condyle [13]. A motorized burr or an awl can be used to demarcate the desired area. With regard to the lateral femoral condyle clock face position, it differs among surgeons [9, 26, 27] and has not shown to be a reliable method.

For identifying the tibial ACL attachment, the remnant fibers should be left intact in order to have a reliable landmark of the previous ACL insertion site. For cases in which the ACL tibial stump is not visible, placing a tibial single-bundle tunnel medial to the midpoint of the anterior horn of the lateral meniscus attachment may be a useful arthroscopic landmark for single-bundle ACL reconstructions (Fig. 17.6).

Lastly, careful attention must be paid in order to preserve the meniscal root insertions because

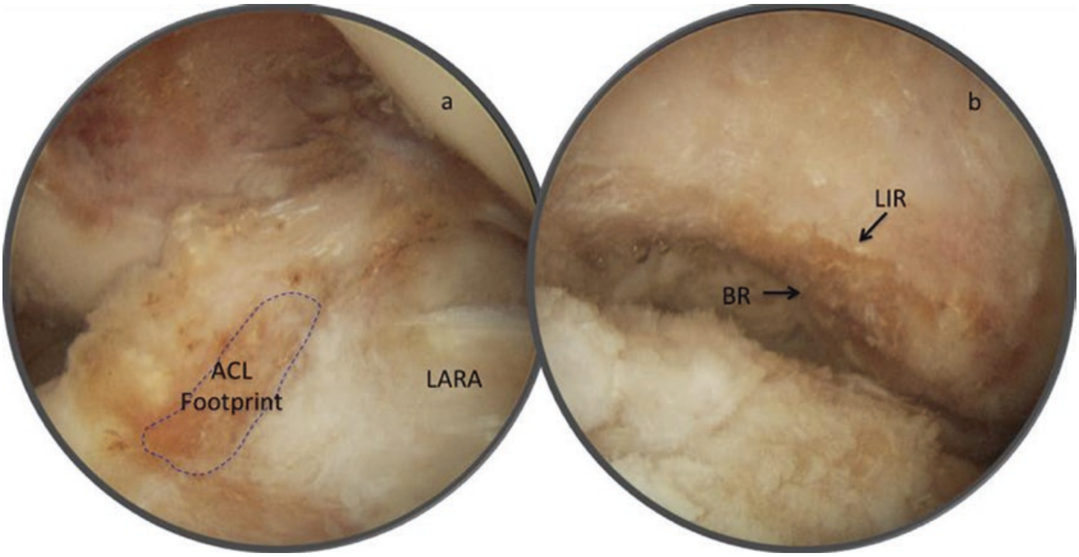
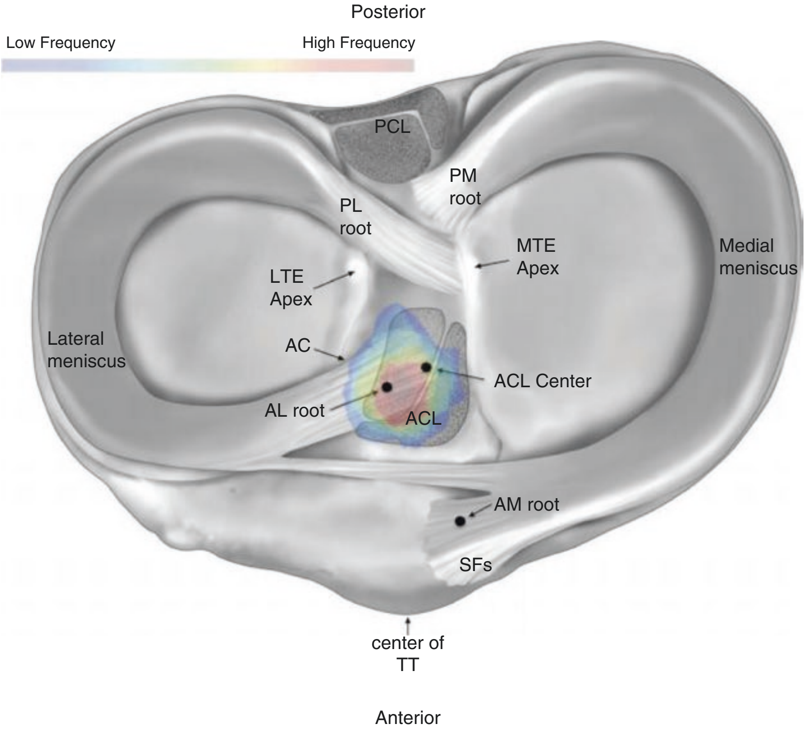


Fig. 17.6 Arthroscopic images of a left knee demonstrating (**a**) the tibial footprint of the ACL and its relationship to the lateral meniscus anterior root attachment (*LARA*) and (**b**) the external femoral condyle in 110° of flexion depicting the lateral intercondylar ridge (*LIR*) and the bifurcate ridge (*BR*)

Fig. 17.7 A diagrammatic representation of the danger zone created using the quantified overlap of the anterolateral (*AL*) meniscal root with the anterior cruciate ligament (*ACL*) superimposed over a qualitative illustration of the tibial plateau (right knee). High frequencies represent areas in which the ACL and AL root were found to overlap in all 12 tested specimens (Reproduced with permission from LaPrade et al. [33])



iatrogenic anterior medial meniscus root [28–30] and posterior lateral meniscus root [31] avulsion can occur due to malposition of the tibial tunnel(s) during ACL reconstruction. Anatomic and biomechanical studies have reported that the attachment fibers of the anterolateral meniscal root course deep to a significant portion of the ACL's tibial attachment fibers [32, 33], and therefore, even an anatomically placed tibial tunnel can disrupt the AL root attachment. AM root attachment was not significantly affected by anatomical ACL tunnel placement in a biomechanical study [30] (Fig. 17.7).

Key Points for a Successful ACL Tunnel Placement

1. Extensive knowledge of the anatomy and relationship with surrounding structures can reduce the risk of tunnel misplacement in ACL reconstruction. Extreme caution should be taken not to damage meniscal roots.
2. Viewing arthroscopic portal should be chosen based on the structure needed to observe (AM portal for lateral femoral wall) in order to diminish optical distortion.
3. Ninety degrees of knee flexion should be maintained when determining graft placement since accuracy of the footprint could be reproduced more accurately. Hyperflexion of the knee is recommended when reaming the femoral tunnels in order to avoid lateral structure damage.

References

1. Ziegler CG, Pietrini SD, Westerhaus BD, Anderson CJ, Wijdicks CA, Johansen S et al (2011) Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. Am J Sports Med 39(4):743–752. doi:10.1177/0363546510387511
2. Steiner M (2009) Anatomic single-bundle ACL reconstruction. Sports Med Arthrosc 17(4):247–251. doi:10.1097/JSA.0b013e3181c0ccf8
3. Hutchinson MR, Ash SA (2003) Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthroscopy 19(9):931–935
4. Farrow LD, Chen MR, Cooperman DR, Victoroff BN, Goodfellow DB (2007) Morphology of the femoral intercondylar notch. J Bone Joint Surg Am 89(10):2150–2155. doi:10.2106/jbjs.f.01191
5. Ferretti M, Ekdahl M, Shen W, Fu FH (2007) Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy 23(11):1218–1225. doi:10.1016/j.arthro.2007.09.008
6. Lu W, Wang D, Zhu W, Li D, Ouyang K, Peng L et al (2015) Placement of double tunnels in acl reconstruction using bony landmarks versus existing footprint remnant: a prospective clinical study with 2-year follow-up. Am J Sports Med 43(5):1206–1214. doi:10.1177/0363546515570850
7. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL (1999) Quantitative analysis of human cruciate ligament insertions. Arthroscopy 15(7):741–749
8. Hensler D, Working ZM, Illingworth KD, Thorhauer ED, Tashman S, Fu FH (2011) Medial portal drilling: effects on the femoral tunnel aperture morphology during anterior cruciate ligament reconstruction. J Bone Joint Surg Am 93(22):2063–2071. doi:10.2106/jbjs.j.01705
9. Siebold R, Ellert T, Metz S, Metz J (2008) Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement – a cadaver study. Arthroscopy 24(5):585–592. doi:10.1016/j.arthro.2007.12.008
10. Hoshino Y, Nagamune K, Yagi M, Araki D, Nishimoto K, Kubo S et al (2009) The effect of intra-operative knee flexion angle on determination of graft location in the anatomic double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 17(9):1052–1060. doi:10.1007/s00167-009-0773-5
11. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH (2011) Size variability of the human anterior cruciate ligament insertion sites. Am J Sports Med 39(1):108–113. doi:10.1177/0363546510377399
12. Kongcharoensombat W, Ochi M, Abouheif M, Adachi N, Ohkawa S, Kamei G et al (2011) The transverse ligament as a landmark for tibial sagittal insertions of the anterior cruciate ligament: a cadaveric study. Arthroscopy 27(10):1395–1399. doi:10.1016/j.arthro.2011.05.019
13. Musahl V, Burkart A, Debski RE, Van Scyoc A, Fu FH, Woo SL (2003) Anterior cruciate ligament tunnel placement: comparison of insertion site anatomy with the guidelines of a computer-assisted surgical system. Arthroscopy 19(2):154–160. doi:10.1053/jars.2003.50001
14. Girgis FG, Marshall JL, Monajem A (1975) The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res 106:216–231
15. Odensten M, Gillquist J (1985) Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. J Bone Joint Surg Am 67(2):257–262
16. Takahashi M, Doi M, Abe M, Suzuki D, Nagano A (2006) Anatomical study of the femoral and tibial insertions of the anteromedial and posterolateral bundles of human anterior cruciate ligament. Am J Sports Med 34(5):787–792. doi:10.1177/0363546505282625
17. Purnell ML, Larson AI, Clancy W (2008) Anterior cruciate ligament insertions on the tibia and femur and their relationships to critical bony landmarks using high-resolution volume-rendering computed tomography. Am J Sports Med 36(11):2083–2090. doi:10.1177/0363546508319896
18. Carson EW, Anisko EM, Restrepo C, Panariello RA, O'Brien SJ, Warren RF (2004) Revision anterior cruciate ligament reconstruction: etiology of failures and clinical results. J Knee Surg 17(3):127–132
19. Hoshino Y, Rothrauff BB, Hensler D, Fu FH, Musahl V (2014) Arthroscopic image distortion-part I: the effect of lens and viewing angles in a 2-dimensional

in vitro model. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3336-3
20. Hoshino Y, Rothrauff BB, Hensler D, Fu FH, Musahl V (2014) Arthroscopic image distortion-part II: the effect of lens angle and portal location in a 3D knee model. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3268-y
21. Rabuck SJ, Middleton KK, Maeda S, Fujimaki Y, Muller B, Araujo PH et al (2012) Individualized anatomic anterior cruciate ligament reconstruction. Arthrosc Tech 1(1):e23–e29. doi:10.1016/j.eats.2011.12.004
22. Shino K, Nakata K, Nakamura N, Toritsuka Y, Nakagawa S, Horibe S (2005) Anatomically oriented anterior cruciate ligament reconstruction with a bone-patellar tendon-bone graft via rectangular socket and tunnel: a snug-fit and impingement-free grafting technique. Arthroscopy 21(11):1402. doi:10.1016/j.arthro.2005.08.017
23. Cha PS, Brucker PU, West RV, Zelle BA, Yagi M, Kurosaka M et al (2005) Arthroscopic double-bundle anterior cruciate ligament reconstruction: an anatomic approach. Arthroscopy 21(10):1275. doi:10.1016/j.arthro.2005.07.018
24. Neven E, D'Hooghe P, Bellemans J (2008) Double-bundle anterior cruciate ligament reconstruction: a cadaveric study on the posterolateral tunnel position and safety of the lateral structures. Arthroscopy 24(4):436–440. doi:10.1016/j.arthro.2007.09.013
25. Siebold R, Ellert T, Metz S, Metz J (2008) Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. Arthroscopy 24(2):154–161. doi:10.1016/j.arthro.2007.08.006
26. Mochizuki T, Muneta T, Nagase T, Shirasawa S, Akita KI, Sekiya I (2006) Cadaveric knee observation study for describing anatomic femoral tunnel placement for two-bundle anterior cruciate ligament reconstruction. Arthroscopy 22(4):356–361. doi:10.1016/j.arthro.2005.09.020
27. Muneta T, Sekiya I, Yagishita K, Ogiuchi T, Yamamoto H, Shinomiya K (1999) Two-bundle reconstruction of the anterior cruciate ligament using semitendinosus tendon with endobuttons: operative technique and preliminary results. Arthroscopy 15(6):618–624. doi:10.1053/ar.1999.v15.0150611
28. Laprade CM, James EW, Engebretsen L, Laprade RF (2014) Anterior medial meniscal root avulsions due to malposition of the tibial tunnel during anterior cruciate ligament reconstruction: two case reports. Knee Surg Sports Traumatol Arthrosc 22(5):1119–1123. doi:10.1007/s00167-014-2868-x
29. Watson JN, Wilson KJ, LaPrade CM, Kennedy NI, Campbell KJ, Hutchinson MR et al (2014) Iatrogenic injury of the anterior meniscal root attachments following anterior cruciate ligament reconstruction tunnel reaming. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3079-1
30. LaPrade CM, Smith SD, Rasmussen MT, Hamming MG, Wijdicks CA, Engebretsen L et al (2015) Consequences of tibial tunnel reaming on the meniscal roots during cruciate ligament reconstruction in a cadaveric model, part 1: the anterior cruciate ligament. Am J Sports Med 43(1):200–206. doi:10.1177/0363546514554769
31. LaPrade CM, Jisa KA, Cram TR, LaPrade RF (2014) Posterior lateral meniscal root tear due to a malpositioned double-bundle anterior cruciate ligament reconstruction tibial tunnel. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3273-1
32. Ellman MB, LaPrade CM, Smith SD, Rasmussen MT, Engebretsen L, Wijdicks CA et al (2014) Structural properties of the meniscal roots. Am J Sports Med 42(8):1881–1887. doi:10.1177/0363546514531730
33. LaPrade CM, Ellman MB, Rasmussen MT, James EW, Wijdicks CA, Engebretsen L et al (2014) Anatomy of the anterior root attachments of the medial and lateral menisci: a quantitative analysis. Am J Sports Med 42(10):2386–2392. doi:10.1177/0363546514544678

18

Functional Analysis of ACL Insertion Site

Jelle P. van der List, Danyal H. Nawabi, and Andrew D. Pearle

18.1 Introduction

Each year more than 100,000 anterior cruciate ligament (ACL) reconstructions are performed in the United States [35]. Failure of single-bundle ACL reconstruction is reported in 11–12 % of all surgeries [13, 71]. Most of these failures are caused by technical errors of which malpositioning of the femoral tunnel is considered as the most common technical error [3, 41, 67, 73]. As a result, there has been an increased focus in the literature on the topic of anatomic ACL reconstruction, with special attention to the femoral tunnel [46, 51].

Several locations and techniques for placement of the ACL graft on the lateral wall of the intercondylar notch have been proposed. Some authors have advocated that complete filling of the femoral footprint is the optimal technique for ACL reconstruction [59, 60]. They have suggested that single-bundle reconstruction is indicated in patients with small femoral footprints and double-bundle reconstruction in patients with larger femoral footprints, with the hypothesis that filling the footprint restores "a maximum amount of stability and function" [30, 60]. Other authors have suggested that a more central position within the femoral footprint is better at restoring native knee kinematics [46, 51, 74]. When translated to a practical setting, in single-bundle reconstruction, the femoral tunnel should be placed centrally between the anteromedial (AM) and posterolateral (PL) bundle, whereas in double-bundle reconstruction, the centers of both bundles are used.

The strategy for filling the entire femoral footprint is, however, difficult when considering the shape of the native ACL. The femoral footprint is 3.5 times larger than the midsubstance of the ACL [17]. Anatomical dissection studies have shown that the shape of the ACL is very different to a tubular ACL graft [43, 56]. At the femoral origin, the ACL has a firm but thin band of fibers attaching perpendicularly to the lateral intercondylar ridge. Further posteriorly at the femoral origin, a fanlike extension of the ligament can be seen that blends with posterior femoral condylar articular cartilage [43, 56]. A few millimeters away from femoral attachment, the ACL is a wide but flat and ribbon-like structure [61, 63, 66]. Because in full extension the posterior cruciate ligament (PCL) occupies the largest part of the intercondylar notch, the flat shape of the ACL prevents impingement on either the lateral femoral condyle or the PCL [24, 25, 66]. Therefore, the technique of filling the entire femoral footprint could cause problems with overstuffing of the intercondylar notch and subsequent impingement. Furthermore, it is not

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possible to restore the three-dimensional ribbon-like shape of the ACL with a tubular graft.

With different single-bundle ACL reconstruction techniques, the coverage of the femoral footprint by the ACL graft is 30–54 % [54]. Therefore, the specific location of a graft within the larger native footprint may be important. The considerations for the most optimal position of the femoral tunnel are discussed in this book chapter. Finally, the identification of the proposed optimal femoral tunnel position at arthroscopy is discussed.

18.2 Considerations

The central position within the femoral ACL footprint, as has been previously proposed by others, may not be the optimal location for graft positioning. The rationale for our proposed femoral tunnel location is discussed with reference to isometry, anatomy, and histology of the native ACL.

18.2.1 Isometry

Isometry is defined as the minimization of elongation of the ACL graft during knee motion. In 1911, Rudolf Fick described in detail the tension pattern of the ACL and found that parts of the ACL were tensioned during range of motion [16]. This finding is known as one of the foundations of the later concept of graft isometry. In 1974, Artmann and Wirth were the first to identify the location at the femoral condyle where the ACL is the most isometric [7]. They suggested that the femoral tunnel should be placed anterior-proximal within the femoral footprint in order to simulate graft isometry [51]. In the following years, ACL graft isometry became considered as one of the most important indicators of a successful ACL reconstruction [57]. Moreover, several instruments, such as the Isometer®, were designed to measure and optimize graft isometry [14].

An isometric graft is thought to result in optimal function and minimizes the risk of graft rupture. Conversely, a nonisometric graft is slack during parts of knee motion and therefore loses its capacity to prevent anterior-posterior laxity [5, 47, 75]. If a nonisometric graft is fixed at the wrong angle or is fixed too anteriorly at the femoral condyle, the graft can cause overconstraint of the knee as the knee is flexed. This overconstraint can cause excessive tension and eventually graft failure [47, 75].

The role of the femoral tunnel position is considered to be of more importance in reproducing isometry than the tibial tunnel position [18]. Many studies have confirmed the importance of the femoral tunnel position in the isometry of the ACL [47, 75, 76]. An anterior (or high) position of the femoral tunnel is considered more isometric than a central or posterior femoral tunnel position (Figs. 18.1 and 18.2) [18, 49, 50]. It has been quantified in biomechanical studies that a graft in an anterior position lengthens up to 4 mm, whereas more graft elongation is seen with a central (up to 8 mm) or posterior position (up to 10 mm) [49]. Zavras et al. confirmed these findings and also showed that the most isometric tunnel position is also located proximally in the footprint [76]. The two most distal positions in the footprint showed the most length change (up to 4–5 mm) during high flexion, whereas more proximal tunnel positions showed only length changes up to 1.5 mm.

The importance of isometry in vivo has been shown by Beynnon et al. [10]. The authors measured the isometry of the graft intraoperatively and divided the patients into a group that did not show graft elongation and a group that did show graft elongation. Immediately after reconstruction, they found no difference between the groups. However, at 5-year follow-up, the group with graft elongation showed more anterior-posterior laxity. These studies made it clear that an isometric position is important in achieving a stable ACL reconstruction without the risk of increased laxity and subsequent graft failure.

Several factors were responsible for the subsequent shift in attention away from isometry, as

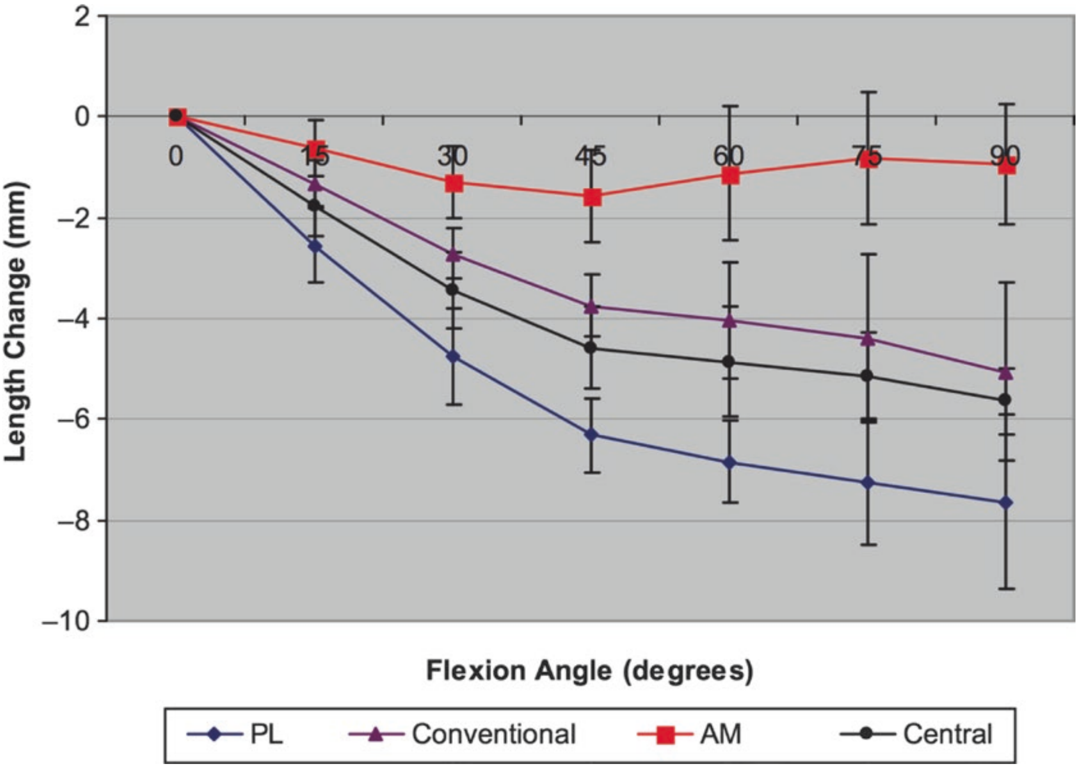

Fig. 18.1 Anisometry profiles of anteromedial (*AM*), posterolateral (*PL*), central, and conventional single-bundle fibers are shown at different flexion angles. Fiber lengths were normalized to zero at full extension for the flexion/extension cycles (Reprinted from Pearle et al. (2008) with kind permission of American Journal of Sports Medicine [49])

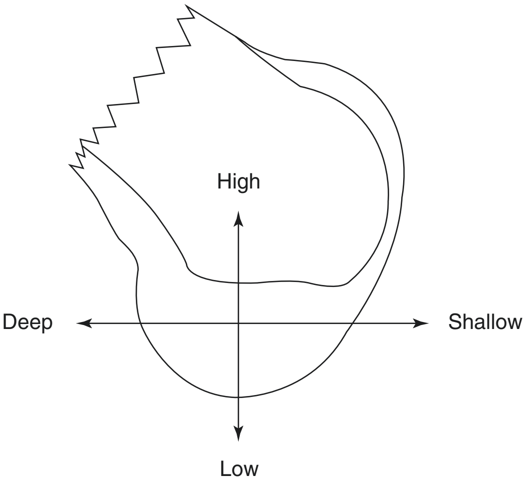

Fig. 18.2 This figure shows the terminology used for the navigation of the femoral footprint. The high position is also called anterior and low position is also called posterior, while the deep location is sometimes referred to as proximal and shallow as distal (Reprinted from Amis et al. (1998) with kind permission of Springer Science and Business Media [5])

the primary goal of ACL reconstruction. Some studies assessed the role of isometry in the native ACL and showed that the ACL is not an isometric structure [6, 31, 37]. Markolf et al. showed with a trial wire that during the last 30° of extension, the length of the ACL increased by approximately 3 mm [37]. In addition, other studies showed that the ACL fibers do not insert at the most isometric point but at the anatomical footprint [4, 31]. It was believed that these anatomical fibers contributed to rotational stability and therefore were of significant importance. These findings resulted in the search for a compromise between a position within the anatomical footprint and a position with isometric characteristics, the so-called anatometry [44]. Although the attention partially shifted toward an anatomic reconstruction, isometry remains an important goal of ACL reconstruction. The more isometric position is located proximal (deep) in the femoral condyle and more anterior (high) [75, 76].

18.2.2 Anatomy

Ernest William Hey Groves (1872–1944) is believed to be the first surgeon who performed a complete ACL reconstruction with the use of a tibial and femoral tunnel [20, 57]. He used the fascia lata as a graft and threaded it through new canals in the femur and tibia. Hey Groves emphasized the role of anatomic reconstruction in proper restoration of knee joint kinematics. In the following decades, more attention was directed toward conservative treatment, primary ACL repair, and isometric tunnel position, and therefore anatomic reconstruction became less important [57].

Over the last decade, however, anatomical femoral tunnel positioning gained popularity, due to recently published data. First of all, the aforementioned studies identified that several ACL fibers inserted within the anatomical footprint and were considered to play an important role in kinematics [4, 31]. Furthermore, the nonanatomic but isometric vertical graft orientation seen with transtibial drilling techniques provided good anterior-posterior stability but suboptimal rotational stability [34, 55, 58]. Finally, in 2005 Musahl et al. compared knee kinematics between an anatomic femoral tunnel position and an isometric femoral tunnel position outside the anatomic footprint in a biomechanical study [45]. Although none of the tunnels fully restored the kinematics to those of a native ACL, they found that the anatomic tunnel position better restored knee kinematics compared to the isometric tunnel position in a simulated Lachman and simulated pivot shift.

In order to determine the anatomy of the footprint, bony landmarks of the femoral ACL insertion have been identified [51]. The lateral intercondylar ridge is an important bony landmark that is located just anterior to the ACL footprint. Clancy Jr. described this bony landmark as the resident's ridge because it can be mistaken for the over-the-top position by inexperienced surgeons [22]. This could result in an anterior positioning of the graft and subsequently failure of the graft [28]. Another osseous landmark, which more recently has been described, is the lateral bifurcate ridge [15]. This ridge connects anteriorly with the lateral intercondylar ridge and posteriorly with the posterior aspect of the femoral cartilage and separates the anteromedial and posterolateral bundles of the ACL [72]. The lateral intercondylar ridge is arthroscopically identified in 88–100 % of the cases, while it is more difficult to identify lateral bifurcate ridge arthroscopically (48–82 %) [15, 70].

These bony landmarks identify the anatomical footprint of the ACL fibers. The anatomical footprint is crescent shaped with the lateral intercondylar ridge as a straight anterior border and the lateral femoral condyle as a convex posterior border [63]. The surface area of the femoral ACL attachment site varies in different studies between 70 and 200 mm^2 [23, 30] and is thought to cover approximately 18 % of the lateral wall of the intercondylar notch [23]. The length of the anatomical footprint varies in several studies between 14 and 18.5 mm and the width between 7 and 11 mm [30].

The shape of the native ACL is more tubular at the midsubstance and is flat, ribbon-like at the femoral end with a thickness of 2–4 mm and width of 10–16 mm (Fig. 18.3) [63]. It is not surprising that with single-bundle reconstruction, the ACL graft can only cover 30–54 % of the femoral footprint [54]. Therefore, some thought must be given to positioning of the ACL graft within the large area of the footprint. With time

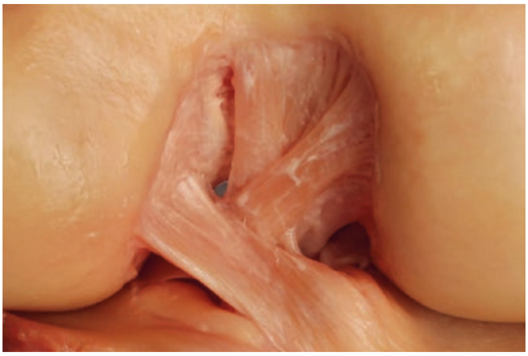

Fig. 18.3 The ribbon shape of the ACL after careful removal of the synovial tissue is shown. The ACL fibers form a flat ribbon 2 mm from its femoral attachment to midsubstance (Reprinted from Śmigielski et al. (2014) with kind permission of Springer Science and Business Media [63])

zero biomechanical studies showing superiority of an anatomic tunnel position [34, 45, 55, 58], it would appear beneficial to place the femoral tunnel within the confines of the footprint in the most isometric location, as opposed to an isometric position that is nonanatomic. Several studies have shown that the region that is both anatomic and isometric is located proximal (deep) and anterior (just posterior of the lateral intercondylar ridge) within the anatomic footprint [76].

18.2.3 Direct Fibers

Over the last few years, there has been an increasing interest in the histological characteristics of the ACL following a study of Iwahashi et al. [27]. The authors in this study identified two categories of fiber insertions at the femoral side of the ACL, with different histological and biomechanical characteristics. The authors described these fibers as the direct and indirect insertions (Fig. 18.4). The direct insertion has a transitional zone between the ligamentous tissue and the femoral insertion, while the indirect insertion lacks this zone. This transitional zone consists of ligamentous tissue, noncalcified cartilage, and calcified cartilage and enables the distribution of loads. Therefore, many authors considered the direct fibers to be biomechanically more important [8, 9, 27]. The indirect fibers are thought to play a role in resisting shear movements by functioning as a dynamic anchorage of soft tissue to the bone [56].

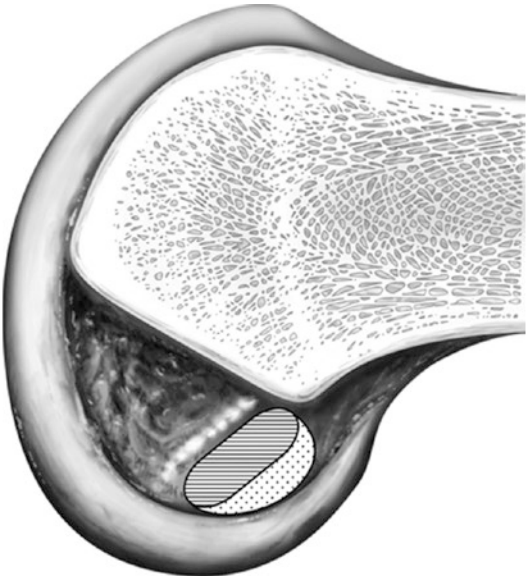

Fig. 18.4 The oval ACL insertion is shown. The direct insertion was located at the anterior of the ACL insertion (*shaded portion*). The width of the direct insertion was narrow. The posterior of the ACL insertion was the indirect insertion (*dotted portion*) (Reprinted from Sasaki et al. (2012) with kind permission of Elsevier [56])

It was noted that the location and orientation of the indirect or “fanlike” fibers did not change through the flexion arc, while the direct fibers did change in location [43]. Pathare et al. examined the biomechanical role of both fiber insertions [48]. They assessed the kinematics of knees with an intact ACL and compared these kinematics with knees in which the indirect fibers were removed. They found that knee kinematics between the intact ACL and the transected indirect fibers did not significantly differ in the simulated Lachman, anterior drawer, and pivot shift test. Upon transection of the direct fibers, a large increase in anterior tibial translation and internal tibial rotation was noted. Another study showed that the direct fibers carry approximately 82–90 % of the load when an anterior drawer force is applied, while the fanlike fibers only contributed to a minor part of the overall load [29]. These studies suggest that the indirect fibers have a much smaller load-bearing function compared to the direct fibers. Therefore, it may be beneficial to aim the femoral tunnel in the region of the direct fibers. Furthermore, it has recently been shown that graft impingement was not significant when placing the femoral tunnel in the direct insertion [69] although this has also been shown in a cadaveric study [26].

The direct fibers form a narrow, linear band zone that inserts just posteriorly to the lateral intercondylar ridge, which means they are located anteriorly within the anatomical femoral footprint [27, 48, 56]. The anterior-posterior thickness of the direct fibers is 5.3 mm (±1.1) [56] and covers approximately 36 % of the anatomical femoral footprint [43]. The indirect fibers insert between the direct fibers and the posterior femoral condylar cartilage, which means a posterior location inside the anatomical femoral footprint.

The anterior-posterior thickness of the indirect fibers is approximately 4.4 mm (±0.5) [56], and they cover approximately 64 % of the surface of the femoral anatomical footprint [43].

Sasaki et al. observed that the direct and indirect fibers are both microscopically and macroscopically identifiable with the positions as described above [56]. Indirect fibers do not contribute much to knee kinematics and load carrying and lack a transitional zone. Therefore, we recommend targeting the region of the direct fibers that consists of a 5 mm thick linear zone bordering the lateral intercondylar ridge and thus anteriorly within anatomical footprint.

18.2.4 Tension Pattern

Another possible explanation for higher failure rates of ACL reconstruction is the tension on the ACL graft. It has been suggested that a higher force on the ACL graft can cause graft failure, loss of fixation, or limited motion [21, 37, 38]. Several studies have shown that the largest tension on the ACL takes place during extension and hyperextension [21, 36]. As the knee moves through the flexion arc, the tension decreases. Markolf et al. compared the forces on the native ACL with forces on the ACL graft and found higher forces on the ACL graft (Fig. 18.5) [36]. They specifically found that in the native ACL, the tension decreased as the knee moves through the flexion arc, but this decline was less pronounced in the ACL graft. The authors found similar results in a second study using different ACL reconstruction techniques [40].

The position of the femoral tunnel is known to play a role on the forces on the ACL graft [21, 32, 38]. Increased graft force can cause overconstraint; posterior, lateral, and external subluxation; and eventually slackening and failure of the graft [42]. Zavras et al. assessed the tension on the ACL graft and the anterior-posterior laxity in different femoral tunnel positions [75]. They compared different tunnel positions in the proximal isometric zone and found that the femoral tunnel location that imparted the lowest tension on ACL graft was located at the anterior-proximal corner inside the anatomical footprint. This position correlates with the previously stated position that is both isometric and anatomic. They found that a more anterior position of the femoral tunnel caused an increased tension pattern in knee flexion and subsequently can cause overconstraint. A more posterior position of the femoral tunnel can cause high tension in extension and slackening of the graft during flexion and thus an increased anterior-posterior laxity. Other studies have confirmed the correlation between several femoral tunnel positions and the tension in the graft [36, 37, 62]. In addition, as stated in the isometry discussion, placing the femoral tunnel more distal would cause an increased length change compared to proximal positioning within the anatomical footprint [76].

Markolf et al. assessed the tensioning of the ACL graft in different ACL reconstruction techniques [40]. They compared the intact ACL with single-bundle ACL reconstruction and with the "fill-the-footprint" ACL reconstruction. Their results showed that the single-bundle technique better restored the graft tension than the fill-the-footprint technique. These biomechanical studies show that the graft tension most optimally approximates the intact ACL graft tension when the femoral tunnel is placed in the anterior-proximal zone of the anatomical footprint.

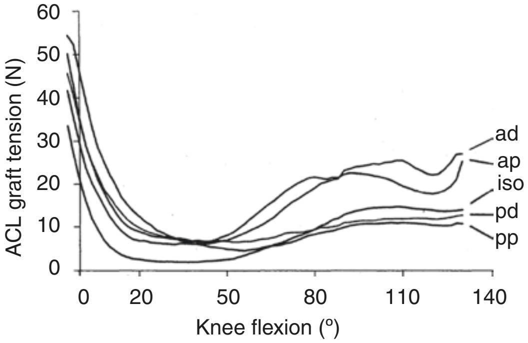

Fig. 18.5 This graph shows the graft tension of the different femoral tunnel position grafts. The pp position indicates the proximal position within the anatomical footprint, while the pd position indicates the distal position within the anatomical footprint. The two anterior positions (ap and ad) were positioned outside the anatomical footprint and show a higher graft tension pattern. The tunnels positioned within the anatomical footprint (pp and pd) and the isokinetic position showed the least graft tension (Reprinted from Zavras et al. (2005) with kind permission of Springer Science and Business Media [75])

18.3 Guidelines for Arthroscopic Surgery

During arthroscopic surgery, it can be challenging to identify the anatomical landmarks and subsequently place the graft in an anatomic and isometric position within the anatomical footprint. To locate the position within the anatomical footprint, we provide some guidelines that can be used during arthroscopic surgery.

18.3.1 Eccentric Position

Several studies have advocated a central position for the ACL within the femoral footprint [19, 34, 58, 74]. Wilson et al. recently advocated a central position of the femoral tunnel [74] in order to capture the function of the anteromedial and posterolateral bundles. However, as previously discussed, there are different loading characteristics for different regions of the femoral footprint. Because of these considerations, we advocate that the femoral tunnel insertion should be placed eccentrically within the anterior-proximal region of the footprint rather than in a more central position. We discussed that a graft in a central position showed more elongation (up to 8 mm) compared with a more anterior position within the footprint (up to 4 mm) and has lower tension in the graft than a central location. Furthermore, this position also occupies the region of the direct ACL fibers. Thus, a central position for the graft would not be optimal with respect to isometry, tension patterns, and biomechanics. Therefore, after identification of the native ACL footprint during arthroscopic surgery, an eccentric anterior-proximal location is recommended to prevent these risk factors of graft failure (Fig. 18.6).

18.3.2 Equidistant

The other guideline that can be used to check whether the proposed femoral tunnel is correctly positioned is the equidistance between anatomical landmarks. The anterior-proximal femoral tunnel position within the anatomical footprint is roughly equidistant between the top of the femoral notch and the bottom of the notch or the most posterior aspect of the femoral cartilage. This point can be easily identified and functions as a last check

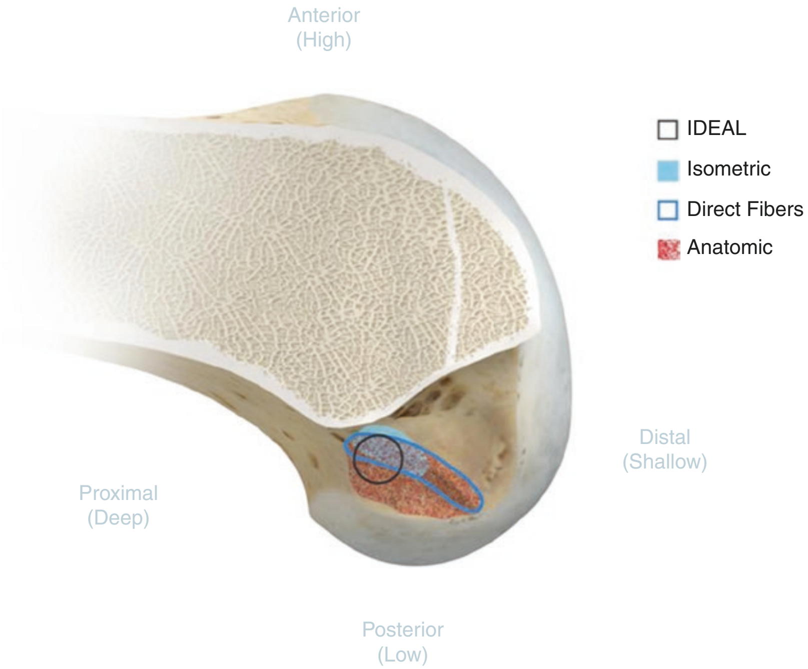

Fig. 18.6 This figure summarizes the ideal tunnel position (*black circle*) since this is in the anatomical footprint and captures both the direct fibers and the most isometric position (Reprinted from Pearle et al. (2015) with kind permission of The American Journal of Orthopedics [48])

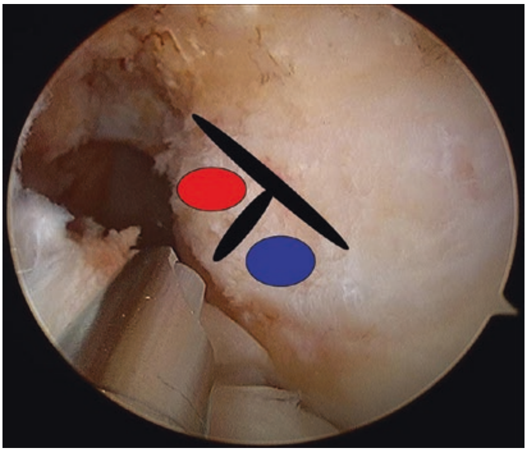

Fig. 18.7 An arthroscopic view of the femoral footprint is shown with the intercondylar ridge (*upper black line*), bifurcate ridge (*lower line* between two colored dots), and the centers of the anteromedial (*red*) and posterolateral (*blue*) bundle

before the femoral tunnel is drilled. Moreover, the bony anatomy of the femoral footprint is not always clear [15, 70]. This equidistant position halfway between the top of the notch and the most posterior aspect of the femoral cartilage can be identified when the osseous landmarks of the anatomical footprint are not entirely clear since these landmarks are outside the footprint (Fig. 18.7).

18.3.3 Transtibial and Anteromedial Technique

There has been much debate about whether the transtibial technique (TT) or the anteromedial (AM) technique should be used for the drilling of the femoral tunnel. With the use of the transtibial technique (TT), the tibial tunnel dictates the femoral tunnel position and can result in a more vertical graft [1, 64, 65]. A more vertical graft is correlated with an increased graft tension [62] and rotational instability [34, 55, 58] although this latter finding has been questioned [39]. With the AM portal drilling technique, also referred to as independent drilling technique, a good identification of the anatomy of femoral footprint is necessary in order to identify the position of the femoral tunnel [68].

Many systematic reviews and meta-analyses have lately been published to determine which technique is superior [2, 12, 33, 52, 53]. The general conclusion is a good femoral tunnel position is possible with both techniques although some studies showed a small preference for the AM or independent drilling technique [2, 12, 33]. However, a Danish registry-based study showed that the revision rate of the AM technique (5.2 %) is higher than the revision rate of the TT technique (3.2 %) [52]. Their explanation was that the introduction of this new and more complex AM technique causes more technical failures, while it is also possible that the femoral tunnel position plays a role. A retrospective in vivo MRI comparison performed by Bowers et al. found no differences between the positions of the femoral tunnel at the femoral condyle [11]. However, a more posterior position of the tibial tunnel in the tibial footprint was necessary to ensure femoral insertion at the anatomical footprint, and therefore the graft obliquity in the sagittal plane was more vertical with the TT technique. This finding is similar to earlier reports [1, 64, 65].

Taking the systematic reviews and meta-analyses into consideration, it seems that an acceptable femoral tunnel position can be achieved with both techniques. Some studies suggest that an AM technique will result in better functional outcomes and a better tunnel positions although the Danish registry showed that the revision rate could be slightly higher with the AM technique.

Conclusion

Due to the large surface area of the anatomic femoral ACL footprint and the inability of a tubular ACL graft to fill the footprint, some thought must be given to positioning of an ACL graft within the confines of the native footprint. Based on the critical review of the literature that we have presented in this chapter, we recommend an anterior (high) and proximal (deep) position within the anatomical femoral footprint. With the femoral tunnel in this location, the graft (I) remains anatomic, (II) is relatively isometric, (III) has low tension, and (IV) is located in the biomechanically advantageous direct insertion.

This position can be identified reliably at arthroscopy and is located just posterior to the lateral intercondylar ridge and proximal (deep) to the lateral bifurcate ridge. Further studies are needed to clarify whether the position we propose in this chapter results in clinically superior outcomes.

References

1. Ahn JH, Lee SH, Yoo JC, Ha HC (2007) Measurement of the graft angles for the anterior cruciate ligament reconstruction with transtibial technique using postoperative magnetic resonance imaging in comparative study. Knee Surg Sports Traumatol Arthrosc 15(11):1293–1300. doi:10.1007/s00167-007-0389-6
2. Alentorn-Geli E, Lajara F, Samitier G, Cugat R (2010) The transtibial versus the anteromedial portal technique in the arthroscopic bone-patellar tendon-bone anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18(8):1013–1037. doi:10.1007/s00167-009-0964-0
3. Allen CR, Giffin JR, Harner CD (2003) Revision anterior cruciate ligament reconstruction. Orthop Clin North Am 34(1):79–98
4. Amis AA, Dawkins GP (1991) Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg Br 73(2):260–267
5. Amis AA, Jakob RP (1998) Anterior cruciate ligament graft positioning, tensioning and twisting. Knee Surg Sports Traumatol Arthrosc 6(Suppl 1):S2–S12
6. Arms SW, Pope MH, Johnson RJ, Fischer RA, Arvidsson I, Eriksson E (1984) The biomechanics of anterior cruciate ligament rehabilitation and reconstruction. Am J Sports Med 12(1):8–18
7. Artmann M, Wirth CJ (1974) Investigation of the appropriate functional replacement of the anterior cruciate ligament (author's transl). Z Orthop Ihre Grenzgeb 112(1):160–165
8. Benjamin M, Evans EJ, Copp L (1986) The histology of tendon attachments to bone in man. J Anat 149:89–100
9. Benjamin M, Moriggl B, Brenner E, Emery P, McGonagle D, Redman S (2004) The "enthesis organ" concept: why enthesopathies may not present as focal insertional disorders. Arthritis Rheum 50(10):3306–3313. doi:10.1002/art.20566
10. Beynnon BD, Uh BS, Johnson RJ, Fleming BC, Renstrom PA, Nichols CE (2001) The elongation behavior of the anterior cruciate ligament graft in vivo. A long-term follow-up study. Am J Sports Med 29(2):161–166
11. Bowers AL, Bedi A, Lipman JD, Potter HG, Rodeo SA, Pearle AD, Warren RF, Altchek DW (2011) Comparison of anterior cruciate ligament tunnel position and graft obliquity with transtibial and anteromedial portal femoral tunnel reaming techniques using high-resolution magnetic resonance imaging. Arthroscopy 27(11):1511–1522. doi:10.1016/j.arthro.2011.07.007
12. Chalmers PN, Mall NA, Cole BJ, Verma NN, Bush-Joseph CA, Bach BR Jr (2013) Anteromedial versus transtibial tunnel drilling in anterior cruciate ligament reconstructions: a systematic review. Arthroscopy 29(7):1235–1242. doi:10.1016/j.arthro.2013.02.015
13. Crawford SN, Waterman BR, Lubowitz JH (2013) Long-term failure of anterior cruciate ligament reconstruction. Arthroscopy 29(9):1566–1571. doi:10.1016/j.arthro.2013.04.014
14. Daniel DM (1987) System for establishing ligament graft orientation and isometry. United States Patent
15. Ferretti M, Ekdahl M, Shen W, Fu FH (2007) Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthroscopy 23(11):1218–1225. doi:10.1016/j.arthro.2007.09.008
16. Fick R (1911) Handbuch der Anatomie und Mechanik der Gelenke. 3 Teil: Spezielle Gelenk- und Muskelmechanik. Gustav Fischer, Jena
17. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL (1999) Quantitative analysis of human cruciate ligament insertions. Arthroscopy 15(7):741–749
18. Hefzy MS, Grood ES, Noyes FR (1989) Factors affecting the region of most isometric femoral attachments: part II: the anterior cruciate ligament. Am J Sports Med 17(2):208–216. doi:10.1177/036354658901700210
19. Heming JF, Rand J, Steiner ME (2007) Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. Am J Sports Med 35(10):1708–1715. doi:10.1177/0363546507304137
20. Hey Groves EW (1917) Operation for repair of the crucial ligaments. Lancet 190:674–675
21. Howell SM, Wallace MP, Hull ML, Deutsch ML (1999) Evaluation of the single-incision arthroscopic technique for anterior cruciate ligament replacement. A study of tibial tunnel placement, intraoperative graft tension, and stability. Am J Sports Med 27(3):284–293
22. Hutchinson MR, Ash SA (2003) Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthroscopy 19(9):931–935
23. Iriuchishima T, Ryu K, Aizawa S, Fu FH (2014) Proportional evaluation of anterior cruciate ligament footprint size and knee bony morphology. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3139-6
24. Iriuchishima T, Shirakura K, Fu FH (2013) Graft impingement in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21(3):664–670. doi:10.1007/s00167-012-2014-6
25. Iriuchishima T, Tajima G, Ingham SJ, Shen W, Horaguchi T, Saito A, Smolinski P, Fu FH (2009) Intercondylar roof impingement pressure after anterior

cruciate ligament reconstruction in a porcine model. Knee Surg Sports Traumatol Arthrosc 17(6):590–594. doi:10.1007/s00167-008-0691-y

26. Iriuchishima T, Tajima G, Ingham SJ, Shen W, Smolinski P, Fu FH (2010) Impingement pressure in the anatomical and nonanatomical anterior cruciate ligament reconstruction: a cadaver study. Am J Sports Med 38(8):1611–1617. doi:10.1177/0363546510363461
27. Iwahashi T, Shino K, Nakata K, Otsubo H, Suzuki T, Amano H, Nakamura N (2010) Direct anterior cruciate ligament insertion to the femur assessed by histology and 3-dimensional volume-rendered computed tomography. Arthroscopy 26(9 Suppl):S13–S20. doi:10.1016/j.arthro.2010.01.023
28. Jaureguito JW, Paulos LE (1996) Why grafts fail. Clin Orthop Relat Res 325:25–41
29. Kawaguchi Y, Kondo E, Takeda R, Akita K, Yasuda K, Amis AA (2015) The role of fibers in the femoral attachment of the anterior cruciate ligament in resisting tibial displacement. Arthroscopy 31(3):435–444. doi:10.1016/j.arthro.2014.08.033
30. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH (2009) A systematic review of the femoral origin and tibial insertion morphology of the ACL. Knee Surg Sports Traumatol Arthrosc 17(3):213–219. doi:10.1007/s00167-008-0709-5
31. Kurosawa H, Yamakoshi K, Yasuda K, Sasaki T (1991) Simultaneous measurement of changes in length of the cruciate ligaments during knee motion. Clin Orthop Relat Res 265:233–240
32. Lewis JL, Lew WD, Engebretsen L, Hunter RE, Kowalczyk C (1990) Factors affecting graft force in surgical reconstruction of the anterior cruciate ligament. J Orthop Res 8(4):514–521. doi:10.1002/jor.1100080407
33. Liu A, Sun M, Ma C, Chen Y, Xue X, Guo P, Shi Z, Yan S (2015) Clinical outcomes of transtibial versus anteromedial drilling techniques to prepare the femoral tunnel during anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-015-3672-y
34. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL (2003) Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. Arthroscopy 19(3):297–304. doi:10.1053/jars.2003.50084
35. Lyman S, Koulouvaris P, Sherman S, Do H, Mandl LA, Marx RG (2009) Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. J Bone Joint Surg Am 91(10):2321–2328. doi:10.2106/JBJS.H.00539
36. Markolf KL, Burchfield DM, Shapiro MM, Cha CW, Finerman GA, Slauterbeck JL (1996) Biomechanical consequences of replacement of the anterior cruciate ligament with a patellar ligament allograft. Part II: forces in the graft compared with forces in the intact ligament. J Bone Joint Surg Am 78(11):1728–1734
37. Markolf KL, Burchfield DM, Shapiro MM, Davis BR, Finerman GA, Slauterbeck JL (1996) Biomechanical consequences of replacement of the anterior cruciate ligament with a patellar ligament allograft. Part I: insertion of the graft and anterior-posterior testing. J Bone Joint Surg Am 78(11):1720–1727
38. Markolf KL, Gorek JF, Kabo JM, Shapiro MS (1990) Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. J Bone Joint Surg Am 72(4):557–567
39. Markolf KL, Jackson SR, McAllister DR (2010) A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test. Am J Sports Med 38(5):912–917. doi:10.1177/0363546509358321
40. Markolf KL, Park S, Jackson SR, McAllister DR (2009) Anterior-posterior and rotatory stability of single and double-bundle anterior cruciate ligament reconstructions. J Bone Joint Surg Am 91(1):107–118. doi:10.2106/jbjs.g.01215
41. MARS-group, Wright RW, Huston LJ, Spindler KP, Dunn WR, Haas AK, Allen CR, Cooper DE, DeBerardino TM, Lantz BB, Mann BJ, Stuart MJ (2010) Descriptive epidemiology of the multicenter ACL revision study (MARS) cohort. Am J Sports Med 38(10):1979–1986. doi:10.1177/0363546510378645
42. Melby A 3rd, Noble JS, Askew MJ, Boom AA, Hurst FW (1991) The effects of graft tensioning on the laxity and kinematics of the anterior cruciate ligament reconstructed knee. Arthroscopy 7(3):257–266
43. Mochizuki T, Fujishiro H, Nimura A, Mahakkanukrauh P, Yasuda K, Muneta T, Akita K (2014) Anatomic and histologic analysis of the mid-substance and fan-like extension fibres of the anterior cruciate ligament during knee motion, with special reference to the femoral attachment. Knee Surg Sports Traumatol Arthrosc 22(2):336–344. doi:10.1007/s00167-013-2404-4
44. Müller W (1983) The knee. Springer, Berlin
45. Musahl V, Plakseychuk A, VanScyoc A, Sasaki T, Debski RE, McMahon PJ, Fu FH (2005) Varying femoral tunnels between the anatomical footprint and isometric positions: effect on kinematics of the anterior cruciate ligament-reconstructed knee. Am J Sports Med 33(5):712–718. doi:10.1177/0363546504271747
46. Narvy SJ, Pearl M, Vrla M, Yi A, Hatch GF 3rd (2015) Anatomy of the femoral footprint of the posterior cruciate ligament: a systematic review. Arthroscopy 31(2):345–354. doi:10.1016/j.arthro.2014.07.004
47. O'Meara PM, O'Brien WR, Henning CE (1992) Anterior cruciate ligament reconstruction stability with continuous passive motion. The role of isometric graft placement. Clin Orthop Relat Res 277:201–209
48. Pathare NP, Nicholas SJ, Colbrunn R, McHugh MP (2014) Kinematic analysis of the indirect femoral insertion of the anterior cruciate ligament: implications for anatomic femoral tunnel placement. Arthroscopy 30(11):1430–1438. doi:10.1016/j.arthro.2014.07.017
49. Pearle AD, Shannon FJ, Granchi C, Wickiewicz TL, Warren RF (2008) Comparison of 3-dimensional obliquity and anisometric characteristics of anterior cruciate ligament graft positions using

surgical navigation. Am J Sports Med 36(8):1534–1541. doi:10.1177/0363546508315536

50. Penner DA, Daniel DM, Wood P, Mishra D (1988) An in vitro study of anterior cruciate ligament graft placement and isometry. Am J Sports Med 16(3):238–243
51. Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH (2012) Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. Arthroscopy 28(6):872–881. doi:10.1016/j.arthro.2011.11.026
52. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC (2013) Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. Arthroscopy 29(1):98–105. doi:10.1016/j.arthro.2012.09.009
53. Riboh JC, Hasselblad V, Godin JA, Mather RC 3rd (2013) Transtibial versus independent drilling techniques for anterior cruciate ligament reconstruction: a systematic review, meta-analysis, and meta-regression. Am J Sports Med 41(11):2693–2702. doi:10.1177/0363546513506979
54. Robert HE, Bouguennec N, Vogeli D, Berton E, Bowen M (2013) Coverage of the anterior cruciate ligament femoral footprint using 3 different approaches in single-bundle reconstruction: a cadaveric study analyzed by 3-dimensional computed tomography. Am J Sports Med 41(10):2375–2383. doi:10.1177/0363546513498989
55. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 15(2):285–293. doi:10.1002/jor.1100150219
56. Sasaki N, Ishibashi Y, Tsuda E, Yamamoto Y, Maeda S, Mizukami H, Toh S, Yagihashi S, Tonosaki Y (2012) The femoral insertion of the anterior cruciate ligament: discrepancy between macroscopic and histological observations. Arthroscopy 28(8):1135–1146. doi:10.1016/j.arthro.2011.12.021
57. Schindler OS (2012) Surgery for anterior cruciate ligament deficiency: a historical perspective. Knee Surg Sports Traumatol Arthrosc 20(1):5–47. doi:10.1007/s00167-011-1756-x
58. Scopp JM, Jasper LE, Belkoff SM, Moorman CT 3rd (2004) The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. Arthroscopy 20(3):294–299. doi:10.1016/j.arthro.2004.01.001
59. Siebold R (2011) The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 19(5):699–706. doi:10.1007/s00167-010-1376-x
60. Siebold R, Schuhmacher P (2012) Restoration of the tibial ACL footprint area and geometry using the Modified Insertion Site Table. Knee Surg Sports Traumatol Arthrosc 20(9):1845–1849. doi:10.1007/s00167-012-1899-4
61. Siebold R, Schuhmacher P, Fernandez F, Smigielski R, Fink C, Brehmer A, Kirsch J (2014) Flat midsubstance of the anterior cruciate ligament with tibial “C”-shaped insertion site. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3058-6
62. Simmons R, Howell SM, Hull ML (2003) Effect of the angle of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on tension of an anterior cruciate ligament graft: an in vitro study. J Bone Joint Surg Am 85-A(6):1018–1029
63. Śmigielski R, Zdanowicz U, Drwięga M, Ciszek B, Ciszkowska-Łysoń B, Siebold R (2014) Ribbon like appearance of the midsubstance fibres of the anterior cruciate ligament close to its femoral insertion site: a cadaveric study including 111 knees. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3146-7
64. Stanford FC, Kendoff D, Warren RF, Pearle AD (2009) Native anterior cruciate ligament obliquity versus anterior cruciate ligament graft obliquity: an observational study using navigated measurements. Am J Sports Med 37(1):114–119. doi:10.1177/0363546508323257
65. Steiner ME, Battaglia TC, Heming JF, Rand JD, Festa A, Baria M (2009) Independent drilling outperforms conventional transtibial drilling in anterior cruciate ligament reconstruction. Am J Sports Med 37(10):1912–1919. doi:10.1177/0363546509340407
66. Triantafyllidi E, Paschos NK, Goussia A, Barkoula NM, Exarchos DA, Matikas TE, Malamou-Mitsi V, Georgoulis AD (2013) The shape and the thickness of the anterior cruciate ligament along its length in relation to the posterior cruciate ligament: a cadaveric study. Arthroscopy 29(12):1963–1973. doi:10.1016/j.arthro.2013.09.007
67. Trojani C, Sbihi A, Djian P, Potel JF, Hulet C, Jouve F, Bussiere C, Ehkirch FP, Burdin G, Dubrana F, Beaufils P, Franceschi JP, Chassaing V, Colombet P, Neyret P (2011) Causes for failure of ACL reconstruction and influence of meniscectomies after revision. Knee Surg Sports Traumatol Arthrosc 19(2):196–201. doi:10.1007/s00167-010-1201-6
68. Tudisco C, Bisicchia S (2012) Drilling the femoral tunnel during ACL reconstruction: transtibial versus anteromedial portal techniques. Orthopedics 35(8):e1166–e1172. doi:10.3928/01477447-20120725-14
69. van der List JP, Zuiderbaan HA, Nawabi DH, Pearle AD (2015) Impingement following anterior cruciate ligament reconstruction: comparing the direct versus indirect femoral tunnel position. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-015-3897-9
70. van Eck CF, Morse KR, Lesniak BP, Kropf EJ, Tranovich MJ, van Dijk CN, Fu FH (2010) Does the lateral intercondylar ridge disappear in ACL deficient patients? Knee Surg Sports Traumatol Arthrosc 18(9):1184–1188. doi:10.1007/s00167-009-1038-z
71. van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH (2012) Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. Am J Sports Med 40(4):800–807. doi:10.1177/0363546511432545
72. Weber WWE (1836) Mechanik der menschlichen Gehwerkzeuge eine anatomisch-physiologische

Untersuchung. Göttingen in der Dieterichschen Buchhandlung

73. Wetzler MJ, Bartolozzi AR, Gillespie MJ, Rubenstein DL, Ciccotti MG, Miller LS (1996) Revision anterior cruciate ligament reconstruction. Oper Tech Orthop 6(3):181
74. Wilson AJ, Yasen SK, Nancoo T, Stannard R, Smith JO, Logan JS (2013) Anatomic all-inside anterior cruciate ligament reconstruction using the translateral technique. Arthrosc Tech 2(2):e99–e104. doi:10.1016/j.eats.2012.12.002
75. Zavras TD, Race A, Amis AA (2005) The effect of femoral attachment location on anterior cruciate ligament reconstruction: graft tension patterns and restoration of normal anterior-posterior laxity patterns. Knee Surg Sports Traumatol Arthrosc 13(2):92–100. doi:10.1007/s00167-004-0541-5
76. Zavras TD, Race A, Bull AMJ, Amis AA (2001) A comparative study of 'isometric' points for anterior cruciate ligament graft attachment. Knee Surg Sports Traumatol Arthrosc 9(1):28–33. doi:10.1007/s001670000170

19

Double-Bundle Anterior Cruciate Ligament Reconstruction

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19.1 Introduction

Complete anterior cruciate ligament (ACL) rupture can lead to recurrent knee instability, meniscal tears, articular cartilage degeneration, and subsequent osteoarthritis [4, 42, 44]. The ACL does not normally heal when torn, so surgical reconstruction is the standard treatment for physically active patients [6, 15]. Reconstruction of the ACL has become a commonly performed procedure, with over 100,000 cases per year in the USA [40]. The objective of ACL reconstruction is to reestablish knee function and prevent future meniscal and chondral damage, which can lead to degenerative changes [7, 29].

The native ACL is composed of the functionally distinct anteromedial (AM) and posterolateral (PL) bundles [12, 19, 48]. Biomechanically, the AM and PL bundles function together to provide stability throughout knee range of motion. The bundles are parallel in extension and cross each other during flexion. The AM bundle is primarily responsible for stabilization of the knee in the anterior-posterior direction, whereas the PL bundle provides rotational support [73]. While single-bundle (SB) reconstruction restores the ACL as one bundle, double-bundle (DB) reconstruction restores both the AM and PL bundles.

Anatomy is the basis of orthopedic surgery. The approach to ACL reconstruction surgery is governed by this principle, and the restoration of normal anatomy is necessary to restore normal function of the knee. The concept of anatomic ACL reconstruction is based on four fundamental principles: (1) restore the two functional bundles of the ACL; (2) restore the native insertion sites of the ACL by placing the tunnels in the true anatomic positions; (3) correctly tension each bundle; and (4) individualize surgery for each patient, so tunnel diameter and graft size are dictated by native insertion sites.

DB ACL reconstruction is one application of the anatomic reconstruction concept. SB reconstruction can also be performed in an anatomic

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Editors' Comments on the Evidence Single- vs Double-Bundle Reconstruction We have included two parts to this chapter, one presenting evidence in favor of double-bundle ACL reconstruction and one in favor of single bundle. As the reader will see, either technique can be supported by the existing literature. There is no clear evidence regarding which procedure has better short- or long-term outcomes, and, therefore, surgeons are recommended to choose the procedure they feel is best for their patient while understanding the pros and cons of each.

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Key Concepts

Single-bundle ACL reconstruction: surgical technique that restores the ACL using a single graft in the form of a single bundle.

Double-bundle ACL reconstruction: surgical technique that restores the ACL using two separate grafts to restore each bundle individually.

Transtibial ACL reconstruction: surgical technique in which the femoral tunnel is drilled through the tibial tunnel. It can be used for single- or double-bundle ACL reconstruction.

Anteromedial portal ACL reconstruction: surgical technique in which the femoral tunnel is drilled inside out through an accessory anteromedial portal, allowing to more accurately reach the femoral insertion site compared to the transtibial technique. It can be used for single- or double-bundle ACL reconstruction.

Two-incision ACL reconstruction: surgical technique in which the femoral tunnel is drilled outside-in through a mini-open incision on the lateral side of the distal femur, also allowing to more accurately reach the femoral insertion site compared to the transtibial procedure. It can be used for single- or double-bundle ACL reconstruction.

Anatomic ACL reconstruction concept: restoration of the ACL to its native dimensions, collagen orientation, and insertion sites. It is a concept that can be applied to different surgical techniques including SB reconstruction, DB reconstruction, augmentation, and ACL revision surgery.

Individualized ACL reconstruction: part of the anatomic ACL reconstruction concept, in which the surgical technique (SB or DB) and graft size is chosen depending on preoperative (MRI) and intraoperative measurements of the patient's native ACL and bony anatomy.

fashion by following the well-defined soft tissue and osseous landmarks and restoring the native insertion site.

Biomechanical studies have demonstrated that while transtibial, nonanatomic ACL reconstruction techniques are successful in limiting anterior tibial translation, they are ineffective for restoring rotatory laxity [10, 11, 49, 70]. In addition, a critical review of the literature reveals that the success rates of ACL reconstruction surgery vary between 69 % and 95 % [6, 8, 17, 75]. The high number of patients who do not return to their previous level of sports activities after surgery further confirms this [11, 13, 15, 18, 76]. This suggests that there remains considerable room for improvement in ACL reconstruction.

19.2 Biomechanical Studies

Biomechanical studies have shown that anatomic DB reconstruction restores knee laxity closer to normal than transtibial SB reconstruction [16, 17, 50, 52, 70, 73, 74, 79].

In a cadaveric study, Musahl et al. [52] found that DB reconstruction offers better anterior and rotational laxity than transtibial SB reconstruction or anatomic SB reconstruction. A mechanized pivot-shift test showed that for intact knees, anterior tibial translation was 1.7 ± 3.0 mm, and for ACL deficient knees, it was 9.7 ± 3.8 mm. After ACL reconstruction, transtibial SB procedure showed an anterior tibial translation of 4.4 ± 1.0 mm, while anatomic SB procedure was much closer to an intact knee at 1.8 ± 1.5 mm. These anatomic and biomechanical considerations have sparked an interest in DB reconstruction techniques following the anatomic ACL reconstruction concept, in which special attention should be given to the restoration of the native insertion site [12, 28, 47, 55, 68].

Morimoto et al. [47] found that DB reconstruction led to increased tibiofemoral contact areas and lower contact pressures than SB procedures. Similarly, Tajima et al. [65] found that DB reconstruction restored patellofemoral contact area and pressure more closely to normal than did SB reconstruction. Some authors have since concluded that DB reconstruction may lead to a lower incidence of osteoarthritis in the injured knee as opposed to SB reconstruction, but this has yet to be determined [62, 80].

Fact Box: Biomechanical Studies

1. DB reconstruction restores knee kinematics closer to the intact ACL knee than SB reconstruction.
2. DB reconstruction restores the in situ forces of the knee closer to normal than SB reconstruction.

19.3 Clinical Studies

Several prospective comparative clinical studies with level I or II evidence have reported superior results of anatomic DB compared with SB reconstruction [2, 3, 6, 26, 29, 31–34, 37, 43, 49, 61, 72, 73, 75, 77]. On the other hand, some studies reported that there is no difference between SB and DB reconstructions [1, 54, 57, 64]. However, for several of the mentioned studies, it remains unclear whether both the SB and DB reconstructions performed were anatomic, restoring the native ACL insertion site.

Some studies have shown that using transtibial drilling leads mostly to nonanatomic, anteriorly positioned femoral tunnels [2, 36, 59, 63]. Furthermore, some studies showed that using the "o'clock" method of femoral tunnel positioning can often lead to misalignment because of the three-dimensional nature of the intercondylar notch [22, 36, 59].

For example, several studies have compared transtibial SB reconstruction with anatomic DB reconstruction [2, 3, 6, 29, 31–34, 43, 49, 61, 68, 69, 72, 75, 77]. In some, transtibial drilling was used for the femoral tunnels in the SB reconstructions and for the AM bundle in the DB reconstructions, with both resulting in tunnel placement outside of the native insertion site [61].

A nonanatomic ACL reconstruction has been related with abnormal knee kinematics, limited range of motion, higher than physiologic graft tension, and, ultimately, graft failure [5, 20, 21, 36, 59, 63, 68, 78].

Kondo et al. [34], in a prospective, comparative study of 328 patients, reported that anatomic DB was superior to SB. The DB group had significantly better results in anteroposterior (AP) and pivot-shift restoration. The anterior laxity was significantly less in the DB reconstruction than in the SB reconstruction (mean 1.2 and 2.5 mm, respectively). In the pivot-shift test, the DB was significantly better than the SB (19% vs. 49%, respectively). But there were no significant differences in terms of IKDC, subjective scores, range of knee motion, muscle torque, and the rate of return to sports activities between the two procedures. In this study, however, the patients were not randomly allocated to the different treatment groups.

Ibrahim et al. [26], in a randomized study, reported that there were no significant differences concerning time between injury, range of movement, and Lysholm knee scores between SB and DB reconstruction. However, the DB group showed significantly better results for the Knee Ligament Arthrometer (MEDmetric, San Diego, CA) KT-1000 measurements, Lachman, anterior drawer test, and pivot-shift test. These results show that in some studies, significantly better results in laxity tests are not necessarily correlated with significantly better clinical outcomes.

Hofbauer et al. [23], in a retrospective study, investigated 55 consecutive patients who underwent SB or DB computer-navigated ACL reconstruction and found that the DB group had significantly better results for rotational laxity, IKDC score, and Lysholm score, but not for AP laxity. These results should consider the retrospective design of this study, the relatively small number of patients, and the associated cost and time of the computer-navigated ACL reconstruction technique.

In a prospective comparative study, Yasuda et al. [75] analyzed anatomic DB, SB, and nonanatomic DB procedures in a total of 72 patients. They reported that the results of anatomic DB were significantly better than SB based on AP and rotational laxity, using KT-2000 and the pivot-shift test, respectively ($P<0.05$). There were no significant differences between the SB and nonanatomic DB groups. Also, they found no significant difference between the three groups with regard to International Knee Documentation Comitee (IKDC) evaluation, range of motion, and muscle torque. This emphasizes that in terms of AP and rotational laxity, anatomic DB reconstruction shows superior results than nonanatomic DB or SB ACL reconstruction.

In a randomized single-blinded study with a minimum follow-up of 24 months, Aglietti et al. [3] reported that DB showed significantly better results than SB reconstruction in terms of AP laxity measured with the KT-2000, visual analog scale, and objective IKDC. But there were no significant differences between the two groups in the pivot-shift and subjective measurements. As with all other studies, nonsignificant results in the pivot-shift measurements should consider the subjectivity of this test, so standardized testing is highly recommended [51].

Park et al. [54], in a prospective study with 113 patients, found that DB reconstruction of the ACL showed no differences in laxity measures, or any other clinical measures of patient satisfaction, when compared with SB reconstruction. However, they used a transtibial technique and the "o'clock" method to place the femoral tunnels. As mentioned before, these methods can lead to nonanatomic reconstruction, making the results discordant with other studies [22, 36, 59].

In contrast with the last study, Hussein et al. [25] looked at the results of the transtibial SB reconstruction group separately from the anatomic SB group and compared them with each other and with those of an anatomic DB group. The femoral tunnels in the anatomic DB group were drilled freehand, independent of the respective tibial tunnel position, and without the use of the "o'clock" reference. They compared AP and rotational laxity (KT-1000 and pivot-shift, respectively), Lysholm score, and IKDC. Results showed that anatomic DB ACL reconstruction is significantly superior to conventional SB ACL reconstruction and better than anatomic SB reconstruction. Also, anatomic SB reconstruction was superior to conventional SB reconstruction. Average side-to-side difference for anterior tibial translation was 1.2 mm in the anatomic DB group, 1.6 mm in the anatomic SB group, and 2.0 mm in the nonanatomic SB group ($p = 0.002$). Negative pivot shift was 93.1 %, 66.7 %, and 41.7 %, respectively ($p \leq 0.003$). This suggests that it is most important to perform ACL reconstructions anatomically, and the addition of a second bundle may provide closer to normal knee laxity. Lysholm score and IKDC didn't show differences between anatomic DB and anatomic SB, but anatomic DB reconstruction had significantly better Lysholm scores compared to transtibial SB reconstruction.

In another study, Hussein et al. [24] compared the results of SB and DB reconstruction using an individualized anatomic technique, which means that during the procedure, the decision for single- or double-bundle reconstruction was made based on the size of the native ACL insertion site. The results showed no significant differences between the groups in terms of Lysholm score (93.9 vs. 93.5), subjective IKDC (93.3 vs. 93.1), anterior tibial translation (1.5 vs. 1.6-mm side-to-side difference), and pivot shift (92 % vs. 90 % negative pivot-shift examination). So they concluded that anatomic DB reconstruction is not superior to anatomic SB reconstruction when an individualized ACL reconstruction technique is used. Given the individualized methodology, nonrandomization should be considered as a limitation in this study. However, the individualized method is a promising technique aimed to achieve the anatomic ACL reconstruction concept, considering the variability of the ACL insertion site area [60].

Recently, in a comparative study of 16,791 patients from the Swedish National Knee Ligament Register, Björnsson et al. [9] compared revision rates and patient-reported outcomes between SB and DB reconstructions. No differences were found in revision rates, Knee injury and Osteoarthritis Outcome Score (KOOS), and EuroQol five dimen-

Fact Box Clinical Studies

1. Different studies have shown no difference in clinical outcomes between SB and DB reconstructions; however, many of the surgical techniques used were not uniform.
2. An anatomic or individualized approach to ACL reconstruction has been shown to have excellent outcomes, whether performed using a SB or DB technique.

sions questionnaire (EQ-5D) between the two techniques over the 7-year observation period. However, these large series have many limitations as lost follow-up, lack of objective outcome measures, selection bias, and variability of reconstruction techniques between surgeons.

19.4 Systematic Reviews and Meta-analysis

Given the evolution of clinical studies comparing SB to DB reconstruction, multiple authors have conducted systematic reviews and meta-analyses comparing both techniques [14, 35, 38, 39, 41, 43, 66, 67, 71, 81]. The results of the meta-analyses have been divergent in their findings regarding the clinical outcomes and knee stability provided by these techniques.

Meredick et al. [43] conducted the first meta-analysis in 2008, finding a small but statistically significant improvement in knee laxity as determined by KT arthrometry in favor of DB reconstruction (0.52-mm side-to-side difference; $p < 0.05$). There were no other statistically significant quantitative or subjective clinical differences between the patients treated with either method.

Tiamklang et al. [66] conducted a meta-analysis that reported no significant difference between DB and SB reconstruction in the subjective IKDC score, Tegner activity score, Lysholm score, adverse effects, or complications, including graft failure (DB: 1.8 %; SB: 2.4 %). However, they found significant differences favoring DB in return to pre-injury level of activity (91 % vs. 82 %), long-term follow-up IKDC (94 % normal vs. 90 % normal), knee laxity measured with KT-1000 arthrometry (mean difference −0.74 mm), and rotational knee laxity tested by the pivot-shift test (normal or nearly normal: 98 % vs. 92 %). There were also significant differences in favor of DB reconstruction for newly occurring meniscal injuries (3.75 % vs. 6.7 %) and traumatic ACL ruptures (0.8 % vs. 5.4 %).

Van Eck et al. [67] reported data from a meta-analysis in favor of DB reconstruction regarding anterior and rotational laxity. KT arthrometer difference was −0.6 mm; there was 64 % risk reduction of positive Lachman, and 69 % risk reduction of positive shift. Similar results were found for the subgroup with more than 2 years' follow-up and anatomic reconstructions. There were no differences in range of motion, Lysholm scores, or complications when compared to SB and DB reconstruction. Most of the included studies were found to have at least one serious limitation in study design.

In another meta-analysis, Li et al. [39] reported that pivot-shift grading, KT grading, and IKDC grading favored DB reconstruction over SB ($P < 0.05$). However, the results didn't reveal differences in other outcomes (IKDC score, KT arthrometer testing, Lysholm score, Tegner score, and complication rate).

Recently, Mascarenhas et al. [41] evaluated the nine available overlapping meta-analyses of SB vs DB reconstruction in an attempt to reconcile conclusions from these meta-analyses. Three of the meta-analyses included level I evidence only [35, 38, 43], and six included level I and level II evidence [14, 39, 66, 67, 71, 81]. Using quality assessment tools for meta-analyses (QUOROM, Oxman–Guyatt scores, and Jadad algorithm) [30, 46, 53, 56], the current highest level of evidence suggests that DB reconstruction provides improved postoperative knee laxity compared with SB reconstruction, as measured by KT arthrometry and pivot-shift testing, although the effect on clinical outcomes and risk of graft failure were not found to be significant.

Of the nine studies included in this review, three of them had high scores, indicating no major flaws with their methodology. These meta-analyses, described previously in this chapter, are the highest current level of evidence available on the subject of SB vs DB ACL reconstruction [39, 66, 67].

Although the best evidence from the highest-quality meta-analyses suggests that DB reconstruction yields superior postoperative knee laxity (based on KT arthrometry and pivot-shift testing), the results should be interpreted cautiously. The KT differences between SB and DB reconstruction may have questionable clinical significance, as the observed difference ranged from 0.56–0.74 mm [66, 67], and there were no

Fig. 19.1 Anatomy of the ACL. (**a**) Anterior view of the knee. Both bundles are shown (*AM* anteromedial, *PL* posterolateral, *PCL* posterior cruciate ligament). (**b**, **c**) ACL femoral (**b**) and tibial (**c**) insertion site. The anatomic femoral insertion site has a deep and low position. ACL insertion site size can vary from individual to individual. Black line demarcates lateral intercondylar ridge ("resident's ridge"). Asterisk shows insertion sites approximate center (Reprinted with permission from Iriuchishima et al. [27] and Middleton et al. [45])

significant differences in functional outcome scores or graft failure rates [39, 66, 67] (Figs. 19.1 and 19.2).

Recently, clinical practice guidelines for management of ACL injuries were published according to the results of a systematic review [58]. Considering "high strength" studies with consistent findings, Carey et al. reported that there is no statistically significant difference between SB and DB reconstruction in postoperative pain, Lysholm score, or IKDC subjective knee score [58]. The clinical practice guideline recommends strongly that the surgeon should use either SB or DB technique, because of the similarity of measured clinical outcomes [58].

Fact Box: Systematic Reviews and Meta-analysis

1. The best evidence from the highest-quality meta-analyses suggests that DB reconstruction yields superior postoperative knee laxity (based on KT arthrometry and pivot-shift testing).
2. Most recent clinical practice guidelines recommend strongly that the surgeon use either SB or DB technique, because of the similarity of measured clinical outcomes.

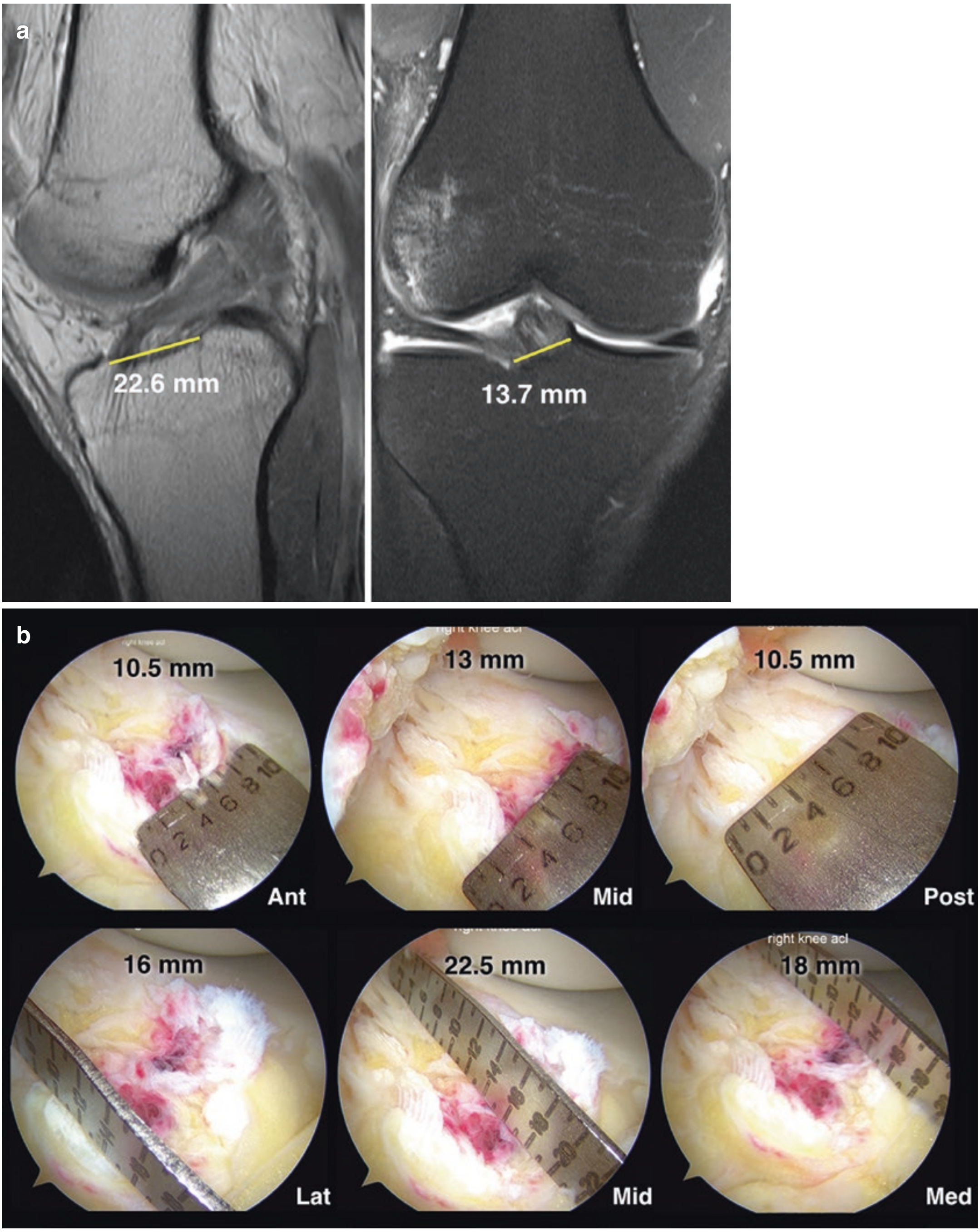

Fig. 19.2 Clinical case. A 23-year-old male sustained a right knee injury during basketball. Physical exam revealed a 2B Lachman, +2 pivot shift, and 5-mm KT-1000 side-to-side difference. (**a**) The sagittal and coronal MRI showed a complete ACL tear. Preoperative measurements showed a large insertion site (tibial sagittal length >18 mm). DB ACL reconstruction was indicated. (**b**) Intraoperative measurements, following the anatomic individualized ACL reconstruction concept, confirmed a large ACL insertion site (tibial sagittal length >18 mm). (**c**) Hamstrings autograft for DB ACL reconstruction D: DB ACL reconstruction (views from lateral, central and anteromedial portals). (**e**) Postoperative 3D reconstructed CT showing the anteromedial (*AM*) and posterolateral (*PL*) tunnel location (*left*: tibia; *right*: femur)

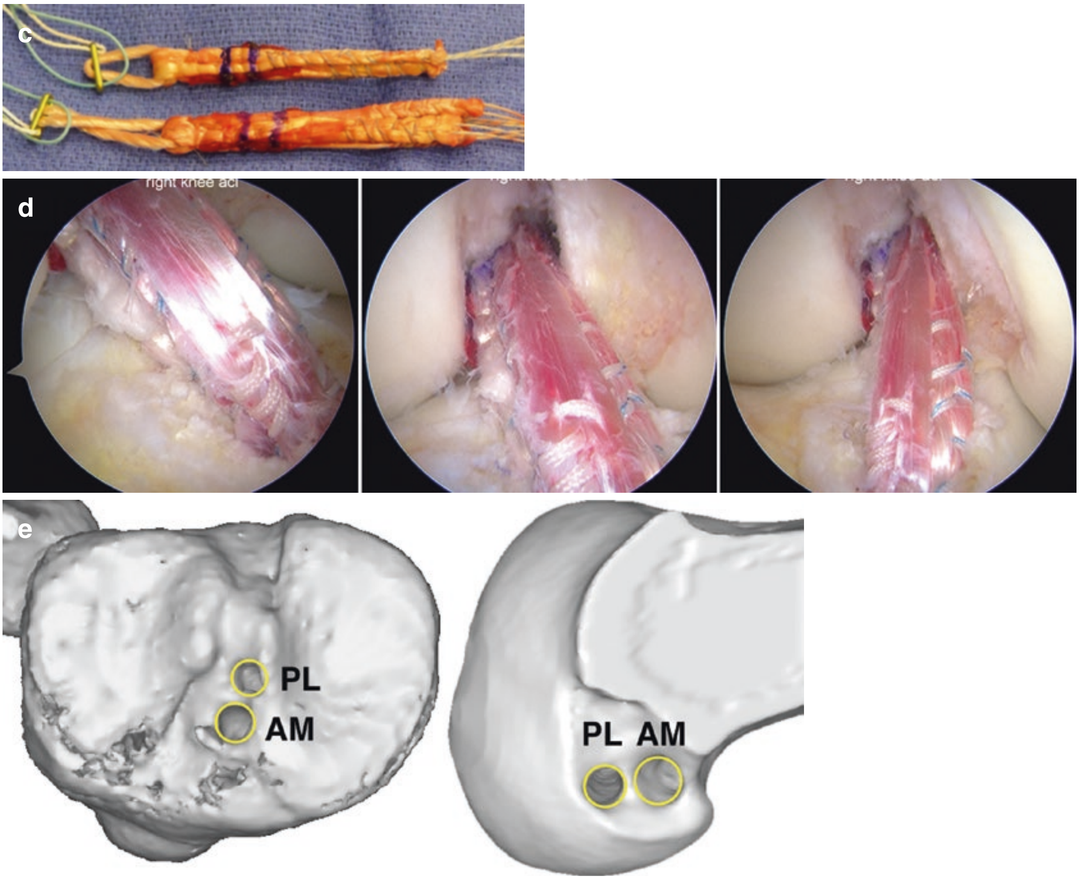

Fig. 19.2 (continued)

19.5 Limitations of This Review

The analysis comparing SB and DB reconstruction studies is limited based on the data from the included studies. The statistical power can be affected by small sample size studies, so in this case a small clinical effect may not be statistically significant. Also, much of the available literature comparing SB and DB reconstruction consists of relatively short-term follow-up, such that a significant difference that only manifests itself in long-term follow-up would be missed in this analysis. An additional limitation lies in the heterogeneity of the included studies. These studies combined the analysis of anatomic and non-anatomic ACL reconstruction techniques. This could potentially alter the laxity measures, in particular, rotational laxity [33].

Conclusions

The current highest level of evidence suggests that DB ACL reconstruction provides better postoperative knee laxity by KT arthrometry and pivot-shift testing when compared with SB ACL reconstruction. The effect on clinical outcomes and risk of graft failure have not found to be significantly different in the systematic reviews and meta-analysis. However, heterogeneity of studies, including tunnel positioning and relatively short-term follow-up, is a limitation to be considered when interpreting this evidence.

Future biomechanical and long-term clinical cohort studies with anatomic ACL reconstruction are needed to further examine the improvement in knee laxity and clinical outcomes afforded by DB reconstruction.

References

1. Adachi N, Ochi M, Uchio Y, Iwasa J, Kuriwaka M, Ito Y (2004) Reconstruction of the anterior cruciate ligament. Single- versus double-bundle multi-stranded hamstring tendons. J Bone Joint Surg Br 86:515–520
2. Aglietti P, Giron F, Cuomo P, Losco M, Mondanelli N (2007) Single-and double-incision double-bundle ACL reconstruction. Clin Orthop Relat Res 454: 108–113
3. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N (2010) Comparison between single-and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. Am J Sports Med 38:25–34
4. Ajuied A, Wong F, Smith C, Norris M, Earnshaw P, Back D, Davies A (2014) Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. Am J Sports Med 42:2242–2252
5. Allen CR, Giffin JR, Harner CD (2003) Revision anterior cruciate ligament reconstruction. Orthop Clin NA 34:79–98
6. Bach BR, Levy ME, Bojchuk J, Tradonsky S, Bush-Joseph CA, Khan NH (1998) Single-incision endoscopic anterior cruciate ligament reconstruction using patellar tendon autograft. Minimum two-year follow-up evaluation. Am J Sports Med 26:30–40
7. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE (2005) Treatment of anterior cruciate ligament injuries, part 2. Am J Sports Med 33: 1751–1767
8. Beynnon BD, Johnson RJ, Fleming BC, Kannus P, Kaplan M, Samani J, Renström P (2002) Anterior cruciate ligament replacement: comparison of bone-patellar tendon-bone grafts with two-strand hamstring grafts. A prospective, randomized study. J Bone Joint Surg 84-A:1503–1513
9. Björnsson H, Andernord D, Desai N, Norrby O, Forssblad M, Petzold M, Karlsson J, Samuelsson K (2015) No difference in revision rates between single- and double-bundle anterior cruciate ligament reconstruction: a comparative study of 16,791 patients from the Swedish National Knee Ligament Register. Arthroscopy 31:659–664
10. Brophy RH, Selby RM, Altchek DW (2006) Anterior cruciate ligament revision: double-bundle augmentation of primary vertical graft. Arthroscopy 22:683. e1–5
11. Cha PS, Brucker PU, West RV, Zelle BA, Yagi M, Kurosaka M, Fu FH (2005) Arthroscopic double-bundle anterior cruciate ligament reconstruction: an anatomic approach. Arthroscopy 21:1275
12. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH (2006) Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. J Bone Joint Surg 88(Suppl 4):2–10
13. Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR (1994) Fate of the ACL-injured patient. A prospective outcome study. Am J Sports Med 22:632–644
14. Desai N, Björnsson H, Musahl V, Bhandari M, Petzold M, Fu FH, Samuelsson K (2014) Anatomic single-versus double-bundle ACL reconstruction: a meta-analysis. Knee Surg Sports Traumatol Arthrosc 22:1009–1023
15. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J (2006) Anatomy of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 14:204–213
16. Edwards A, Bull AMJ, Amis AA (2007) The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament: part 1: tibial attachment. Knee Surg Sports Traumatol Arthrosc 15:1414–1421
17. Fithian DC, Paxton EW, Stone ML, Luetzow WF, Csintalan RP, Phelan D, Daniel DM (2005) Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. Am J Sports Med 33:335–346
18. Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR (2003) Arthroscopic anterior cruciate ligament reconstruction: a metaanalysis comparing patellar tendon and hamstring tendon autografts. Am J Sports Med 31:2–11
19. Girgis FG, Marshall JL, Monajem A (1975) The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res (106):216–231
20. Harner CD, Giffin JR, Dunteman RC, Annunziata CC, Friedman MJ (2001) Evaluation and treatment of recurrent instability after anterior cruciate ligament reconstruction. Instr Course Lect 50:463–474
21. Heming JF, Rand J, Steiner ME (2007) Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. Am J Sports Med 35:1708–1715, American Orthopaedic Society for Sports Medicine
22. Hensler D, Illingworth KD, Fu FH (2010) Principle considerations in anatomic ACL reconstruction. Arthroscopy 26:1414–1415
23. Hofbauer M, Valentin P, Kdolsky R, Ostermann RC, Graf A, Figl M, Aldrian S (2010) Rotational and translational laxity after computer-navigated single- and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18:1201–1207
24. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH (2012) Individualized anterior cruciate ligament surgery: a prospective study comparing anatomic single- and double-bundle reconstruction. Am J Sports Med 40:1781–1788
25. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH (2012) Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate

ligament reconstruction: 281 cases with 3- to 5-year follow-up. Am J Sports Med 40:512–520

26. Ibrahim SAR, Hamido F, Al Misfer AK, Mahgoob A, Ghafar SA, Alhran H (2009) Anterior cruciate ligament reconstruction using autologous hamstring double bundle graft compared with single bundle procedures. J Bone Joint Surg Br 91:1310–1315, British Editorial Society of Bone and Joint Surgery
27. Iriuchishima T, Shirakura K, Fu FH (2013) Graft impingement in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21: 664–670
28. Ishibashi Y, Tsuda E, Tazawa K, Sato H, Toh S (2005) Intraoperative evaluation of the anatomical double-bundle anterior cruciate ligament reconstruction with the OrthoPilot navigation system. Orthopedics 28:s1277–s1282
29. Jacobsen K (1977) Osteoarthrosis following insufficiency of the cruciate ligaments in man. A clinical study. Acta Orthop Scand 48:520–526
30. Jadad AR, Cook DJ, Browman GP (1997) A guide to interpreting discordant systematic reviews. Can Med Assoc J 156:1411–1416
31. Järvelä T (2007) Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective, randomize clinical study. Knee Surg Sports Traumatol Arthrosc 15:500–507, Springer-Verlag
32. Järvelä T, Moisala A-S, Sihvonen R, Järvelä S, Kannus P, Järvinen M (2008) Double-bundle anterior cruciate ligament reconstruction using hamstring autografts and bioabsorbable interference screw fixation: prospective, randomized, clinical study with 2-year results. Am J Sports Med 36:290–297, American Orthopaedic Society for Sports Medicine
33. Kondo E, Merican AM, Yasuda K, Amis AA (2011) Biomechanical comparison of anatomic double-bundle, anatomic single-bundle, and nonanatomic single-bundle anterior cruciate ligament reconstructions. Am J Sports Med 39:279–288
34. Kondo E, Yasuda K, Azuma H, Tanabe Y, Yagi T (2008) Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. Am J Sports Med 36:1675–1687, American Orthopaedic Society for Sports Medicine
35. Kongtharvonskul J, Attia J, Thamakaison S, Kijkunasathian C, Woratanarat P, Thakkinstian A (2013) Clinical outcomes of double- vs single-bundle anterior cruciate ligament reconstruction: a systematic review of randomized control trials. Scand J Med Sci Sports 23:1–14
36. Kopf S, Forsythe B, Wong AK, Tashman S, Anderst W, Irrgang JJ, Fu FH (2010) Nonanatomic tunnel position in traditional transtibial single-bundle anterior cruciate ligament reconstruction evaluated by three-dimensional computed tomography. J Bone Joint Surg Am 92:1427–1431
37. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH (2011) Size variability of the human anterior cruciate ligament insertion sites. Am J Sports Med 39: 108–113
38. Li X, Xu C-p, Song J-q, Jiang N, Yu B (2013) Single-bundle versus double-bundle anterior cruciate ligament reconstruction: an up-to-date meta-analysis. Int Orthop 37:213–226
39. Li Y-L, Ning G-Z, Wu Q, Wu Q-L, Li Y, Hao Y, Feng S-Q (2014) Single-bundle or double-bundle for anterior cruciate ligament reconstruction: a meta-analysis. Knee 21:28–37
40. Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR, Paletta GA (2014) Incidence and trends of anterior cruciate ligament reconstruction in the United States. Am J Sports Med 42:2363–2370, American Orthopaedic Society for Sports Medicine
41. Mascarenhas R, Cvetanovich GL, Sayegh ET, Verma NN, Cole BJ, Bush-Joseph C, Bach Jr. BR (2015) Does double-bundle anterior cruciate ligament reconstruction improve postoperative knee stability compared with single-bundle techniques? A systematic review of overlapping meta-analyses. Arthroscopy 31:1185–1196
42. Mascarenhas R, Tranovich M, Karpie JC, Irrgang JJ, Fu FH, Harner CD (2010) Patellar tendon anterior cruciate ligament reconstruction in the high-demand patient: evaluation of autograft versus allograft reconstruction. Arthroscopy 26:S58–S66
43. Meredick RB, Vance KJ, Appleby D, Lubowitz JH (2008) Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis. Am J Sports Med 36:1414–1421, American Orthopaedic Society for Sports Medicine
44. Meuffels DE, Favejee MM, Vissers MM, Heijboer MP, Reijman M, Verhaar JAN (2009) Ten year follow-up study comparing conservative versus operative treatment of anterior cruciate ligament ruptures. A matched-pair analysis of high level athletes. Br J Sports Med 43:347–351
45. Middleton KK, Hamilton T, Irrgang JJ, Karlsson J, Harner CD, Fu FH (2014) Anatomic anterior cruciate ligament (ACL) reconstruction: a global perspective. Part 1. Knee Surg Sports Traumatol Arthrosc 22:1467–1482
46. Moher D, Cook DJ, Eastwood S, Olkin I, Rennie D, Stroup DF (1999) Improving the quality of reports of meta-analyses of randomised controlled trials: the QUOROM statement. Quality of reporting of meta-analyses. Lancet 354:1896–1900
47. Morimoto Y, Ferretti M, Ekdahl M, Smolinski P, Fu FH (2009) Tibiofemoral joint contact area and pressure after single- and double-bundle anterior cruciate ligament reconstruction. Arthroscopy 25:62–69
48. Mott HW (1983) Semitendinosus anatomic reconstruction for cruciate ligament insufficiency. Clin Orthop Relat Res (172):90–92
49. Muneta T, Koga H, Mochizuki T, Ju Y-J, Hara K, Nimura A, Yagishita K, Sekiya I (2007) A prospective randomized study of 4-strand semitendinosus tendon anterior cruciate ligament reconstruction comparing

single-bundle and double-bundle techniques. Arthrosc : J Arthrosc Relat Surg 23:618–628

50. Murawski CD, van Eck CF, Irrgang JJ, Tashman S, Fu FH (2014) Operative treatment of primary anterior cruciate ligament rupture in adults. J Bone Joint Surg Am 96:685–694
51. Musahl V, Hoshino Y, Ahldén M, Araujo P, Irrgang JJ, Zaffagnini S, Karlsson J, Fu FH (2012) The pivot shift: a global user guide. Knee Surg Sports Traumatol Arthrosc 20:724–731
52. Musahl V, Voos JE, O'Loughlin PF, Choi D, Stueber V, Kendoff D, Pearle AD (2010) Comparing stability of different single- and double-bundle anterior cruciate ligament reconstruction techniques: a cadaveric study using navigation. Arthroscopy 26:S41–S48
53. Oxman AD, Guyatt GH (1991) Validation of an index of the quality of review articles. J Clin Epidemiol 44:1271–1278
54. Park S-J, Jung YB, Jung H-J, Jung H-J, Shin HK, Kim E, Song K-S, Kim G-S, Cheon H-Y, Kim S (2010) Outcome of arthroscopic single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a preliminary 2-year prospective study. Arthroscopy 26:630–636
55. Pombo MW, Shen W, Fu FH (2008) Anatomic double-bundle anterior cruciate ligament reconstruction: where are we today? Arthroscopy 24:1168–1177
56. Poolman RW, Abouali JAK, Conter HJ, Bhandari M (2007) Overlapping systematic reviews of anterior cruciate ligament reconstruction comparing hamstring autograft with bone-patellar tendon-bone autograft: why are they different? J Bone Joint Surg 89:1542–1552
57. Sastre S, Popescu D, Núñez M, Pomes J, Tomas X, Peidro L (2010) Double-bundle versus single-bundle ACL reconstruction using the horizontal femoral position: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc 18:32–36
58. Shea KG, Carey JL, Richmond J, Sandmeier R, Pitts RT, Polousky JD, Chu C, Shultz SJ, Ellen M, Smith A, LaBella CR, Anderson AF, Musahl V, Meyer GD, Jevsevar D, Bozic KJ, Shaffer W, Cummins D, Murray JN, Patel N, Shores P, Woznica A, Martinez Y, Gross L, Sevarino K, American Academy of Orthopaedic S (2015) The American Academy of Orthopaedic Surgeons evidence-based guideline on management of anterior cruciate ligament injuries. J Bone Joint Surg Am 97(8):672–674
59. Shen W, Forsythe B, Ingham SM, Honkamp NJ, Fu FH (2008) Application of the anatomic double-bundle reconstruction concept to revision and augmentation anterior cruciate ligament surgeries. J Bone Joint Surg Am 90(Suppl 4):27S–37S
60. Siebold R (2011) The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 19:699–706
61. Siebold R, Dehler C, Ellert T (2008) Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Arthroscopy 24:137–145
62. Song E-K, Seon J-K, Yim J-H, Woo S-H, Seo H-Y, Lee K-B (2013) Progression of osteoarthritis after double- and single-bundle anterior cruciate ligament reconstruction. Am J Sports Med 41:2340–2346
63. Steiner ME, Battaglia TC, Heming JF, Rand JD, Festa A, Baria M (2009) Independent drilling outperforms conventional transtibial drilling in anterior cruciate ligament reconstruction. Am J Sports Med 37: 1912–1919
64. Streich NA, Friedrich K, Gotterbarm T, Schmitt H (2008) Reconstruction of the ACL with a semitendinosus tendon graft: a prospective randomized single blinded comparison of double-bundle versus single-bundle technique in male athletes. Knee Surg Sports Traumatol Arthrosc 16:232–238, Springer-Verlag
65. Tajima G, Iriuchishima T, Ingham SJM, Shen W, van Houten AH, Aerts MM, Shimamura T, Smolinski P, Fu FH (2010) Anatomic double-bundle anterior cruciate ligament reconstruction restores patellofemoral contact areas and pressures more closely than nonanatomic single-bundle reconstruction. Arthroscopy 26:1302–1310
66. Tiamklang T, Sumanont S, Foocharoen T, Laopaiboon M (2012) Double-bundle versus single-bundle reconstruction for anterior cruciate ligament rupture in adults. Cochrane Database Syst Rev 11:CD008413, Wiley
67. van Eck CF, Kopf S, Irrgang JJ, Blankevoort L, Bhandari M, Fu FH, Poolman RW (2012) Single-bundle versus double-bundle reconstruction for anterior cruciate ligament rupture: a meta-analysis – does anatomy matter? Arthroscopy 28:405–424
68. van Eck CF, Lesniak BP, Schreiber VM, Fu FH (2010) Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthroscopy 26:258–268
69. van Eck CF, Schreiber VM, Mejia HA, Samuelsson K, van Dijk CN, Karlsson J, Fu FH (2010) "Anatomic" anterior cruciate ligament reconstruction: a systematic review of surgical techniques and reporting of surgical data. Arthroscopy 26:S2–S12
70. Woo SLY, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH (2002) The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon. A cadaveric study comparing anterior tibial and rotational loads. J Bone Joint Surg 84-A:907–914
71. Xu M, Gao S, Zeng C, Han R, Sun J, Li H, Xiong Y, Lei G (2013) Outcomes of anterior cruciate ligament reconstruction using single-bundle versus double-bundle technique: meta-analysis of 19 randomized controlled trials. Arthroscopy 29:357–365
72. Yagi M, Kuroda R, Nagamune K, Yoshiya S, Kurosaka M (2007) Double-bundle ACL reconstruction can improve rotational stability. Clin Orthop Relat Res 454:100–107

73. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SLY (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30:660–666
74. Yamamoto Y, Hsu W-H, Woo SLY, Van Scyoc AH, Takakura Y, Debski RE (2004) Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. Am J Sports Med 32:1825–1832
75. Yasuda K, Tanabe Y, Kondo E, Kitamura N, Tohyama H (2010) Anatomic double-bundle anterior cruciate ligament reconstruction. Arthroscopy 26:S21–S34
76. Yunes M, Richmond JC, Engels EA, Pinczewski LA (2001) Patellar versus hamstring tendons in anterior cruciate ligament reconstruction: a meta-analysis. Arthroscopy 17:248–257
77. Zaffagnini S, Bruni D, Marcheggiani Muccioli GM, Bonanzinga T, Lopomo N, Bignozzi S, Marcacci M (2011) Single-bundle patellar tendon versus non-anatomical double-bundle hamstrings ACL reconstruction: a prospective randomized study at 8-year minimum follow-up. Knee Surg Sports Traumatol Arthrosc 19:390–397
78. Zantop T, Diermann N, Schumacher T, Schanz S, Fu FH, Petersen W (2008) Anatomical and nonanatomical double-bundle anterior cruciate ligament reconstruction: importance of femoral tunnel location on knee kinematics. Am J Sports Med 36: 678–685
79. Zelle BA, Vidal AF, Brucker PU, Fu FH (2007) Double-bundle reconstruction of the anterior cruciate ligament: anatomic and biomechanical rationale. J Am Acad Orthop Surg 15:87–96
80. Zhang Z, Gu B, Zhu W, Zhu L (2014) Double-bundle versus single-bundle anterior cruciate ligament reconstructions: a prospective, randomized study with 2-year follow-up. Eur J Orthop Surg Traumatol 24:559–565
81. Zhu Y, Tang R-K, Zhao P, Zhu S-S, Li Y-G, Li J-B (2013) Double-bundle reconstruction results in superior clinical outcome than single-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc 21:1085–1096

Single Bundle Reconstruction is Preferred to Double Bundle

20

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20.1 Introduction

Anterior cruciate ligament (ACL) reconstruction is a common procedure in the USA, with approximately 250,000 reconstructions performed annually [1]. The objective of ACL reconstruction is to restore knee stability by controlling pathologic tibial anterior translation and internal rotation. Historically, the first ACL reconstructions were extra-articular and mainly focused on reducing rotational laxity [2]. The poor results of these isolated extra-articular procedures led to the development of intra-articular ACL reconstruction techniques [3]. As arthroscopy was developed and subsequently utilized in ACL reconstruction, many practitioners began to utilize transtibial femoral tunnel drilling technique, which provided excellent control of AP translation, but offered less effective rotational control [4]. More recently, intra-articular techniques have focused on restoration of native ligament anatomy through the use of independent femoral and tibial tunnel drilling techniques with the goal of restoring better control of both tibial rotation and anterior translation [5]. Double-bundle ACL reconstruction techniques have been developed to further improve control of knee laxity and mimic native anatomy [6]. While this technique makes anatomical and intuitive sense, it has yet to be shown that this translates to improved functional outcomes. The current literature does not definitively support the need for a double-bundle ACL reconstruction.

20.2 ACL Anatomy and Its Restoration

The recent examination of ACL anatomy has not only focused on the origin and insertion of the ligament but also evaluated the functional anatomy of the ligament itself. The concept of the ACL as two functional bundles has been particularly useful in improving our understanding of ligament function [7]. The anteromedial bundle has been described as mostly isometric and functions primarily to control anterior tibial translation throughout knee range of motion, while the smaller posterolateral bundle functions primarily to control tibial internal rotation near full knee extension [8]. This improved understanding of anatomy and function led to the development of double-bundle ACL reconstruction techniques with the hope of

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restoring better knee biomechanics and providing more rotational control, ultimately leading to better patient function.

It is important to consider that the anatomic double-bundle framework is not the only approach to the anatomy of the ACL. Recent work by Smigielski and colleagues has described the ACL as a ribbonlike structure without a clear anatomical demarcation between the function bundles [9, 10]. These data should not been seen as in conflict with the double-bundle functional concept, but rather represent a different understanding of the anatomy that contributes to its function. The concept that two distinct anatomical structures are not necessarily required to restore the multiple functions of the ACL is not a new one. Shino et al. described the use of a single graft with rectangular bone blocks to reproduce ACL anatomy and function years ago [11]. Jacobi et al. described this same concept in a cadaveric model with similar findings [12]. These studies show that rotational control may be achievable with a single ACL graft, allowing continued application of the double-bundle functional concept without a strict replication of the double-bundle anatomy. These anatomic studies do not provide direct evidence for which reconstruction method should be used, rather they provide a framework from which new techniques can be developed and subsequently evaluated through biomechanical and clinical studies.

20.3 Biomechanical Studies

Several biomechanical studies have been conducted in order to determine which reconstruction technique provides the best control of AP and rotational knee laxity. Numerous authors have demonstrated that nonanatomic reconstruction techniques with a vertical femoral tunnel result in poorer control of tibial internal rotation [6, 13, 14]. A particularly well-done study by Musahl et al. evaluated laxity following an anatomical single-bundle (ASB) reconstruction of the anteromedial bundle and a nonanatomical single-bundle (NASB) ACL reconstruction technique and compared these results to those obtained following an anatomical double-bundle (DB) reconstruction [15]. No difference was found between the intact ACL, DB, and ASB groups for the Lachman test or the pivot-shift test. In terms of better reproducing the intact ACL biomechanics, the ASB was nearly identical to the intact ACL for both the Lachman and pivot-shift test, whereas the DB slightly overconstrained the knee (Lachman anterior translation IACL 5.3 mm, ASB 5.2 mm, DB 4.8 mm; pivot-shift anterior translation IACL 1.7 mm, ASB 1.8 mm, DB −1.7 mm; pivot-shift rotation IACL 5.9°, ASB 4.2°, DB 4.1°). Of note, the NASB technique provided significantly less AP and rotational control than either of the anatomic techniques. This study demonstrates that anatomical tunnel placement has a much larger effect on the restoration of knee kinematics than the number of bundles that are reconstructed.

Another biomechanical study by Markolf et al. demonstrated that a single-bundle reconstruction can restore normal knee kinematics during a simulated pivot-shift test [16]. They also noted that while the addition of a posterolateral bundle further decreased tibial internal rotation near full knee extension, this was achieved at the expense of higher graft forces in the posterolateral bundle and less physiologic kinematics. If not properly tensioned, the double-bundle reconstruction led to overconstraint of the knee in external rotation.

It is important to note that all biomechanical studies, regardless of the quality of design, have significant limitations. First, they are unable to truly replicate the loading conditions seen in the living, functioning knee. These studies therefore may not be able to detect differences in the techniques that could be clinically important for patients. Further, they only represent time-zero data. It is unknown what effects graft stretching and remodeling will have on the biomechanics of each graft over time. The best insights into these questions come from clinical outcome studies.

20.4 Clinical Studies

Many prospective, randomized studies (RCT) have compared double-bundle reconstruction to single-bundle reconstruction with a mix of results. Some have demonstrated improved Lachman, pivot-shift, KT-1000, and objective IKDC results with double-bundle techniques, but patient-reported outcome measured generally identifies no differences between the two techniques. The issue with interpretation of the findings of these studies is that many different reconstruction techniques were used, especially in the single-bundle groups. Some authors used patellar tendon grafts [17, 18], some used hamstring grafts [11, 19–28], and others used allografts [29]. Most studies chose transtibial drilling techniques [17, 21–24, 26, 27, 29], while some studies used independent tunnel drilling [19, 20, 25, 30]. Although these are all well-described and accepted techniques for ACL reconstruction, it is hard to truly compare anatomic single- and double-bundle reconstructions given the variability of the literature. Most of these studies failed to demonstrate significant clinical differences between single- and double-bundle techniques, and one must consider the small size of many of these studies, leading to the potential for type 2 error [17, 21, 22, 24, 25, 27, 29].

In a recent 2015 high-quality double-blind RCT, Mohtadi et al. analyzed the results of 330 patients divided in three groups: patellar tendon single-bundle reconstruction (PT), hamstring single-bundle reconstruction (HT), and double-bundle reconstruction (DB) [1, 31, 32]. Anatomic tunnel placement was performed in each of the three groups using the same methods. The 2-year follow-up rate was 97.5 %. The authors stratified their randomization by chronicity to avoid selection bias. The surgery was blinded to the patient by using the same anteromedial incision regardless of technique. In this study, the PT group had significantly less anterior translation than the HT and DB groups (1.9 mm vs. 3.0 mm for HT and 2.7 mm for DB), but there was no difference in terms of the pivot shift. There were no differences in any of the functional outcome scores (ACL-QOL, IKDC, Tegner, Cincinnati). The PT group had significantly less traumatic re-injuries when combining partial and complete re-ruptures (3 % vs. 11 % for HT and 10 % for DB). The study also looked at atraumatic graft failures defined as the presence of a grade 2 or 3 pivot shift or at least 6 mm of AP translation. There were no significant differences between the groups in the incidence of atraumatic failures, and there was no significant difference in terms of complications. There was significantly more kneeling pain in the PT group (17 % vs. 9 % for HT and 4 % for DB). The DB technique took significantly more time (mean 88 min vs. 68 min for HT and 75 min for PT). Ultimately, none of the outcome measures in this high-quality study demonstrated improved clinical outcomes with a double-bundle reconstruction technique.

20.5 Meta-analysis

In a 2012 Cochrane review comparing double-bundle to single-bundle reconstruction, 17 RCTs and quasi-randomized studies were included involving 1433 patients [33]. Most studies had an average 2-year follow-up. According to the authors of the review, all trials had methodological weaknesses and were at risk of bias due to poor randomization strategy and lack of allocation concealment. Data for pooling individual outcomes were only available for 54 % of the participants, leaving 774 patients from nine studies for meta-analysis. In addition, many of the studies utilized different surgical techniques, with the majority using a transtibial drilling technique [17, 21–24, 26, 27, 29]. There were no significant differences between the two groups at a 2-year follow-up for IKDC score, Tegner activity score, Lysholm score, or Cincinnati knee score. There were no statistically significant differences in terms of graft failure or any other adverse events. The return to pre-injury level of activity favored the double-bundle group in five studies [20, 21, 23, 30, 34, 35]. The pooled difference effect of patients having normal or nearly normal IKDC knee examination was significantly in favor of the double-bundle group at more than 2-year follow-up. At 5-year follow-up, however, the difference was not statistically significant [18]. Knee anterior laxity, as measured by the KT-1000, was significantly in favor of DB in pooled data from eight studies [11, 20–22, 26, 27, 30]. However, in pooled data from five studies using the KT-2000, there was no significant difference [18, 19, 24, 34, 35]. There was no significant difference in the Lachman test, but there was a significant difference in favor of the DB group for

Table 20.1 Patient-reported outcome scores by surgical technique

Author and year	Patient-reported outcome score	Single-bundle	Double-bundle	Significance
Kondo et al. (2008) [36]	Lysholm	96.5 ± 5.8	97.3 ± 3.3	$p > 0.05$
Siebold et al. (2008) [26]	Lysholm	93 ± 6	90 ± 9	$p = 0.22$
	IKDC	90 ± 10	88 ± 10	$p = 0.42$
Streich et al. (2008) [27]	Lysholm	91.5 ± 6.3	91.8 ± 7.3	$p > 0.05$
	IKDC	88.6 ± 6.5	89.5 ± 6.4	$p > 0.05$
Aglietti et al. (2010) [20]	IKDC	78 ± 15	83 ± 15	$p = 0.05$
Park et al. (2010) [24]	IKDC	69.8 ± 19.8	76.8 ± 15.3	$p = 0.14$
Sastre et al. (2010) [25]	IKDC	81 ± 6	80 ± 8	$p = 0.52$
Volpi et al. (2010) [17]	Lysholm	95	99.5	$p = 0.38$
Araki et al. (2011) [21]	Lysholm	96 ± 3.6	95 ± 6.3	$p > 0.05$
Misonoo et al. (2012) [22]	Lysholm	93.1 ± 3.5	93.8 ± 2.6	$p > 0.05$
Suomalainen et al. (2012) [28]	Lysholm	86 ± 13	90 ± 9	$p > 0.05$
Mohtadi et al. (2015) [1]	IKDC	84.6 ± 13.8	84.2 ± 11.8	$p = 0.82$
	ACL-QOL	82.5 ± 17.7	82.4 ± 17.5	$p = 0.59$

IKDC International Knee Documentation Committee, *ACL-QOL* Anterior Cruciate Ligament Quality of Life Score

the pivot shift. Because of conflicting data and risk of bias, the authors of the study concluded that there was insufficient evidence to determine the relative effects of double- vs single-bundle ACL reconstruction.

Conclusion

Even though double-bundle reconstructions are an attractive option from a conceptual standpoint, many biomechanical studies suggest that an anatomic single-bundle reconstruction can reliably restore knee stability similar to an intact ACL. The decreased tibial internal rotation noted in some studies with double-bundle reconstructions may actually overconstrain the knee and does not correlate with better functional outcomes. Much of the literature favoring double-bundle reconstructions has been in comparison to nonanatomic single-bundle reconstructions. Moving forward, more data is required specifically focusing on long-term outcomes of anatomic single-bundle and double-bundle reconstructions to determine if there is indeed an advantage to reconstructing both bundles. Considering that double-bundle reconstructions are more costly, take more time, and involve a significant learning curve, single-bundle reconstructions remain the standard of care (Table 20.1).

References

1. Mohtadi N, Chan D, Barber R, Oddone Paolucci E (2015) A randomized clinical trial comparing patellar tendon, hamstring tendon, and double-bundle ACL reconstructions: patient-reported and clinical outcomes at a minimal 2-year follow-up. Clin J Sport Med: Off J Can Acad Sport Med 25:321–331
2. Bertoia JT, Urovitz EP, Richards RR, Gross AE (1985) Anterior cruciate reconstruction using the MacIntosh lateral-substitution over-the-top repair. J Bone Joint Surg Am 67:1183–1188
3. Johnston DR, Baker A, Rose C, Scotland TR, Maffulli N (2003) Long-term outcome of MacIntosh reconstruction of chronic anterior cruciate ligament insufficiency using fascia lata. J Orthop Sci: Off J Jpn Orthop Assoc 8:789–795
4. Robin BN, Jani SS, Marvil SC, Reid JB, Schillhammer CK, Lubowitz JH (2015) Advantages and disadvantages of transtibial, anteromedial portal, and outside-in femoral tunnel drilling in single-bundle anterior cruciate ligament reconstruction: a systematic review. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 31:1412–1417
5. Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, Debski RE (2004) Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. Am J Sports Med 32:1825–1832
6. Yasuda K, van Eck CF, Hoshino Y, Fu FH, Tashman S (2011) Anatomic single- and double-bundle anterior cruciate ligament reconstruction, part 1: basic science. Am J Sports Med 39:1789–1799
7. Shen W, Forsythe B, Ingham SM, Honkamp NJ, Fu FH (2008) Application of the anatomic double-bundle

reconstruction concept to revision and augmentation anterior cruciate ligament surgeries. J Bone Joint Surg Am 90(Suppl 4):20–34
8. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE (2004) Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. J Orthop Res: Off Publ Orthop Res Soc 22:85–89
9. Smigielski R, Zdanowicz U, Drwiega M, Ciszek B, Ciszkowska-Lyson B, Siebold R (2015) Ribbon like appearance of the midsubstance fibres of the anterior cruciate ligament close to its femoral insertion site: a cadaveric study including 111 knees. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 23:3143–3150
10. Siebold R, Schuhmacher P, Fernandez F, Smigielski R, Fink C, Brehmer A, Kirsch J (2015) Flat midsubstance of the anterior cruciate ligament with tibial "C"-shaped insertion site. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 23:3136–3142
11. Muneta T, Koga H, Mochizuki T, Ju YJ, Hara K, Nimura A, Yagishita K, Sekiya I (2007) A prospective randomized study of 4-strand semitendinosus tendon anterior cruciate ligament reconstruction comparing single-bundle and double-bundle techniques. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 23:618–628
12. Jacobi M, Magnussen RA, Villa V, Demey G, Neyret P (2012) The concept of double bundle ACL simulation with a single bundle patellar tendon graft. A cadaveric feasibility study. Sports Med Arthrosc Rehabil Ther Technol: SMARTT 4:19
13. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH (2002) The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon. A cadaveric study comparing anterior tibial and rotational loads. J Bone Joint Surg 84-a:907–914
14. Zelle BA, Vidal AF, Brucker PU, Fu FH (2007) Double-bundle reconstruction of the anterior cruciate ligament: anatomic and biomechanical rationale. J Am Acad Orthop Surg 15:87–96
15. Musahl V, Voos JE, O'Loughlin PF, Choi D, Stueber V, Kendoff D, Pearle AD (2010) Comparing stability of different single- and double-bundle anterior cruciate ligament reconstruction techniques: a cadaveric study using navigation. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 26:S41–S48
16. Markolf KL, Park S, Jackson SR, McAllister DR (2008) Simulated pivot-shift testing with single and double-bundle anterior cruciate ligament reconstructions. J Bone Joint Surg Am 90:1681–1689
17. Volpi P, Cervellin M, Denti M, Bait C, Melegati G, Quaglia A, de Girolamo L (2010) ACL reconstruction in sports active people: transtibial DB technique with ST/G vs. transtibial SB technique with BPTB: preliminary results. Injury 41:1168–1171
18. Zaffagnini S, Bruni D, Marcheggiani Muccioli GM, Bonanzinga T, Lopomo N, Bignozzi S, Marcacci M (2011) Single-bundle patellar tendon versus non-anatomical double-bundle hamstrings ACL reconstruction: a prospective randomized study at 8-year minimum follow-up. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 19:390–397
19. Adachi N, Ochi M, Uchio Y, Iwasa J, Kuriwaka M, Ito Y (2004) Reconstruction of the anterior cruciate ligament. Single- versus double-bundle multistranded hamstring tendons. J Bone Joint Surg Br 86:515–520
20. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N (2010) Comparison between single-and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. Am J Sports Med 38:25–34
21. Fujita N, Kuroda R, Matsumoto T, Yamaguchi M, Yagi M, Matsumoto A, Kubo S, Matsushita T, Hoshino Y, Nishimoto K, Araki D, Kurosaka M (2011) Comparison of the clinical outcome of double-bundle, anteromedial single-bundle, and posterolateral single-bundle anterior cruciate ligament reconstruction using hamstring tendon graft with minimum 2-year follow-up. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 27:906–913
22. Misonoo G, Kanamori A, Ida H, Miyakawa S, Ochiai N (2012) Evaluation of tibial rotational stability of single-bundle vs. anatomical double-bundle anterior cruciate ligament reconstruction during a high-demand activity – a quasi-randomized trial. Knee 19: 87–93
23. Ibrahim SA, Hamido F, Al Misfer AK, Mahgoob A, Ghafar SA, Alhran H (2009) Anterior cruciate ligament reconstruction using autologous hamstring double bundle graft compared with single bundle procedures. J Bone Joint Surg 91:1310–1315
24. Park SJ, Jung YB, Jung HJ, Jung HJ, Shin HK, Kim E, Song KS, Kim GS, Cheon HY, Kim S (2010) Outcome of arthroscopic single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a preliminary 2-year prospective study. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 26:630–636
25. Sastre S, Popescu D, Nunez M, Pomes J, Tomas X, Peidro L (2010) Double-bundle versus single-bundle ACL reconstruction using the horizontal femoral position: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 18:32–36
26. Siebold R, Dehler C, Ellert T (2008) Prospective randomized comparison of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 24:137–145
27. Streich NA, Friedrich K, Gotterbarm T, Schmitt H (2008) Reconstruction of the ACL with a semitendinosus tendon graft: a prospective randomized single blinded comparison of double-bundle versus single-bundle technique in male athletes. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 16:232–238
28. Suomalainen P, Jarvela T, Paakkala A, Kannus P, Jarvinen M (2012) Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 5-year results. Am J Sports Med 40:1511–1518

29. Seon JK, Park SJ, Lee KB, Yoon TR, Seo HY, Song EK (2009) Stability comparison of anterior cruciate ligament between double- and single-bundle reconstructions. Int Orthop 33:425–429
30. Suomalainen P, Moisala AS, Paakkala A, Kannus P, Jarvela T (2011) Double-bundle versus single-bundle anterior cruciate ligament reconstruction: randomized clinical and magnetic resonance imaging study with 2-year follow-up. Am J Sports Med 39: 1615–1622
31. Mohtadi N, Barber R, Chan D, Paolucci EO (2015) Complications and adverse events of a randomized clinical trial comparing 3 graft types for acl reconstruction. Clin J Sport Med Off J Can Acad Sport Med
32. Mohtadi N, Chan D, Barber R, Paolucci EO (2015) Reruptures, reinjuries, and revisions at a minimum 2-year follow-up: a randomized clinical trial comparing 3 graft types for ACL reconstruction. Clin J Sport Med: Off J Can Acad Sport Med
33. Tiamklang T, Sumanont S, Foocharoen T, Laopaiboon M (2012) Double-bundle versus single-bundle reconstruction for anterior cruciate ligament rupture in adults. Cochrane Database Syst Rev 11:Cd008413
34. Zaffagnini S, Bruni D, Russo A, Takazawa Y, Lo Presti M, Giordano G, Marcacci M (2008) ST/G ACL reconstruction: double strand plus extra-articular sling vs double bundle, randomized study at 3-year follow-up. Scand J Med Sci Sports 18:573–581
35. Wang JQ, Ao YF, Yu CL, Liu P, Xu Y, Chen LX (2009) Clinical evaluation of double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: a prospective, randomized and controlled study. Chin Med J 122:706–711
36. Kondo E, Yasuda K, Azuma H, Tanabe Y, Yagi T (2008) Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. Am J Sports Med 36:1675–1687

21

Outside-in Creation of the Anatomical Femoral Tunnel(s)

Konsei Shino and Luigi Adriano Pederzini

21.1 Introduction

While lateral femoral incision(s) are required, the outside-in technique is the gold standard for creating anatomical femoral tunnel during the anatomical ACL reconstruction (ACLR) because of the following reasons: (1) it is applicable to any knees and to any types of graft, (2) good view is consistently obtained on the ACL femoral attachment site while drilling, (3) good fixation is achieved with an interference screw or cortical fixations, (4) there is no risk of damage to the articular cartilage of the medial femoral condyle, and (5) no deep flexion is required.

It is one of the authors (KS)'s policy to create the tunnel(s) inside the femoral attachment area located far back in the lateral wall of the notch to make the aperture(s) robust [1–3]. Thus, a big round tunnel of 10 mm or greater which destroys border of the attachment area or resident's ridge is not created [4, 5] but a single rectangular tunnel or two continuous round tunnels inside the area [6, 7]. However, the other author (LP) prefers to create round tunnels.

21.2 Set-Up, Portals, Exposure of the Femoral Attachment Area

The distal thigh is kept horizontal using a leg holder with the calf hung down with gravity (Fig. 21.1). In addition to the routine anterolateral (AL) and anteromedial (AM) portals, the far anteromedial (FAM) portal which is 2–2.5 cm posterior to the anteromedial portal and just above the medial meniscus is created [8] (Fig. 21.2). This portal makes it possible for instruments to get more perpendicular access to the ACL femoral attachment area on the lateral wall of the notch while viewing around the area through the AM portal.

The fibrous tissues including ACL stump on superior-posterior half of the lateral wall of the intercondylar notch is thoroughly removed using a radiofrequency device through the FAM portal while viewing via the AM portal. Mechanical shavers may not be utilized in order to preserve subtle undulation of the bony surface around the attachment area. After cleaning up, the crescent-shaped attachment area is clearly delineated by the resident's ridge,

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anteriorly; proximal cartilage margin, superiorly; and posterior cartilage margin, posteriorly [1, 2, 9] (Fig. 21.3).

Fig. 21.1 Positioning. The distal thigh is kept horizontal using a leg holder with the calf hung down by gravity

21.3 Creation of Two Femoral Tunnels for Hamstring Tendon Graft

The outside-in technique is suitable for cortical fixation, because the buttons could sit on the harder distal femoral cortex and because the tunnels are longer.

After exposure of the ACL femoral attachment area, the area is transversely divided into two portions: upper proximal portion for the anteromedial (AM) graft and lower posterior portion for the posterolateral (PL) graft. The centers of the two parts are marked with an awl (Fig. 21.4a). With the anterolateral entry femoral guide (Smith&Nephew # 6901189, or 7210984) through the AL portal, two guide pins are drilled from the lateral cortex to the marked centers through small skin incisions of 1 cm in length.

The two pins are overdrilled with cannulated drill-bits of diameter matched with the grafts' diameter in outside-in fashion through a 7-mm skin-muscle protecting cannula (Smith & Nephew #6901106) [6] (Fig. 21.4b).

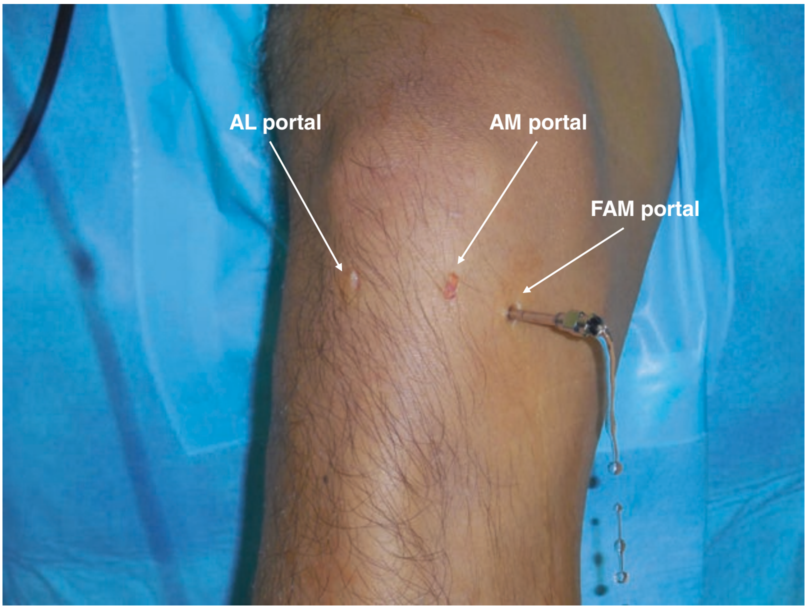

Fig. 21.2 Three arthroscopic portals. In addition to the routine anterolateral (*AL*) and anteromedial (*AM*) portals, the far anteromedial (*FAM*) portal which is 2–2.5 cm posterior to the anteromedial portal and just above the medial meniscus is created

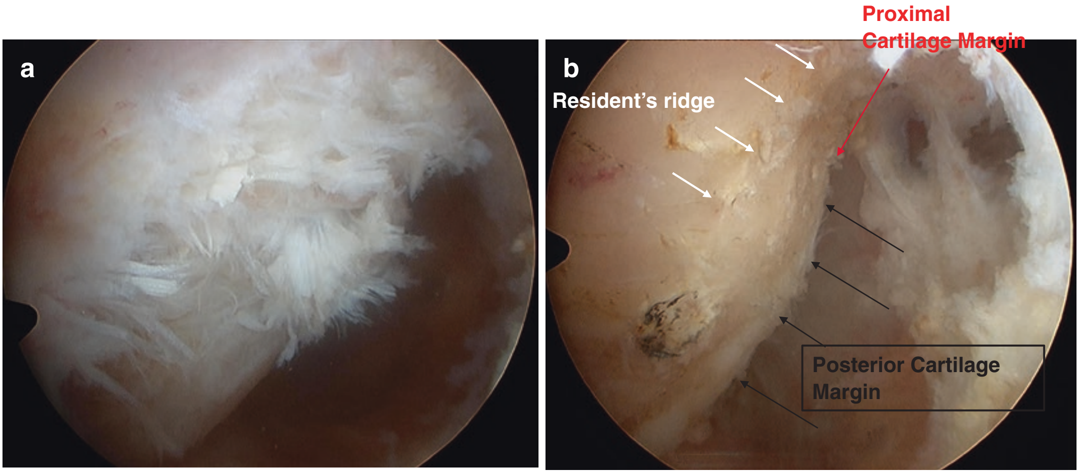

Fig. 21.3 Visualization of the ACL femoral attachment area. (**a**) The femoral attachment area covered with fibrous tissues viewed through the anteromedial portal. (**b**) The femoral attachment area with fibrous tissues thoroughly removed. The area is delineated by the resident's ridge, proximal cartilage margin, and posterior cartilage margin

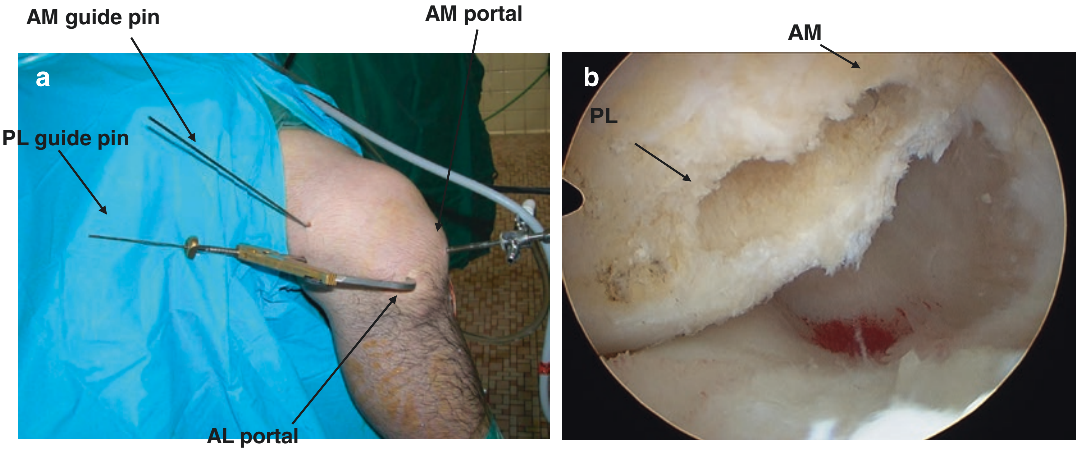

Fig. 21.4 Creation of two femoral tunnel in outside-in fashion. (**a**) Two guide pins are drilled into the center of anterior and posterior halves of the ACL attachment area from the lateral femoral cortex with the anterolateral entry femoral guide (Smith & Nephew # 6901189, or 7210984) via the anterolateral portal. (**b**) Created two tunnel apertures inside the femoral attachment area

21.4 Femoral Tunnel Creation for 10-mm Wide Bone-Patellar Tendon-Bone Graft

21.4.1 Rectangular Tunnel (KS)

This approach is especially recommended for the knee with passive flexion of less than 140°to avoid blowout of the tunnel. Viewing the ACL femoral attachment area via the AM portal, two points are marked with a 5-mm distance in the center of the attachment area along its long axis to the resident's ridge using RF device or a micro-fracture awl. A central guide pin is drilled through a small lateral femoral incision into the center of the area from the lateral femoral cortex with the antero-lateral entry femoral guide (Smith&Nephew # 6901189, or 7210984) via the AL portal (Fig. 21.5). A 11-mm skin protection cannula is installed over the guide pin via 2-cm lateral femoral incision (Fig. 21.6a). With the aid of a 10-mm in-line offset drill guide, two guide pins are drilled parallel to the central pin along the long axis of the attachment area or the

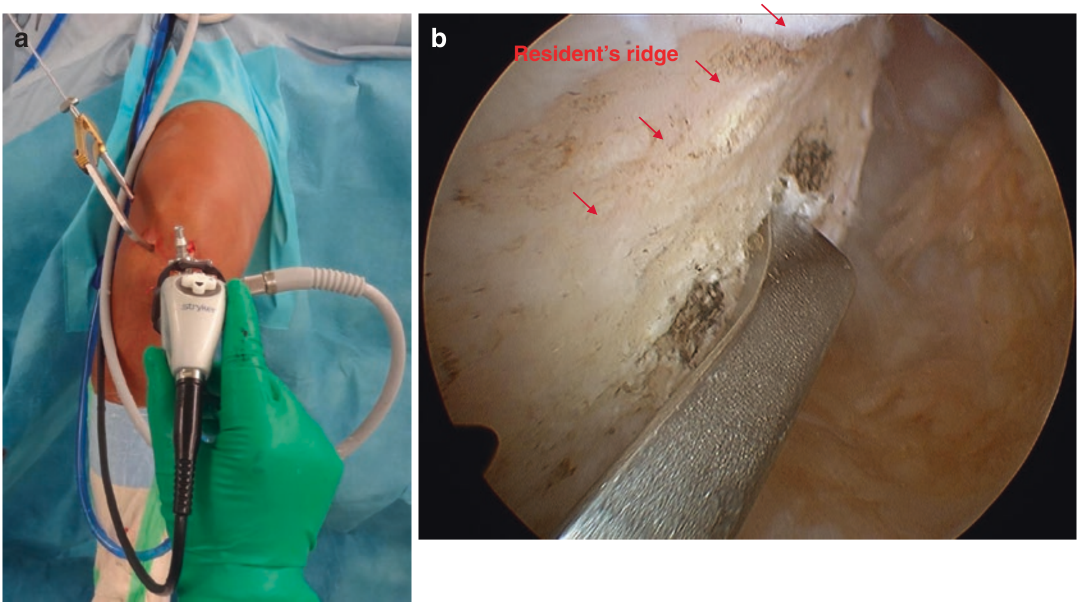

Fig. 21.5 Outside-in drilling of a guide pin to the center of the ACL attachment area. (**a**) A central guide pin is drilled into the center from the lateral femoral cortex with the anterolateral entry femoral guide (Smith&Nephew # 6901189, or 7210984) via the anterolateral portal. (**b**) Drill guide tip at the center of the ACL femoral attachment area viewed via the anteromedial portal

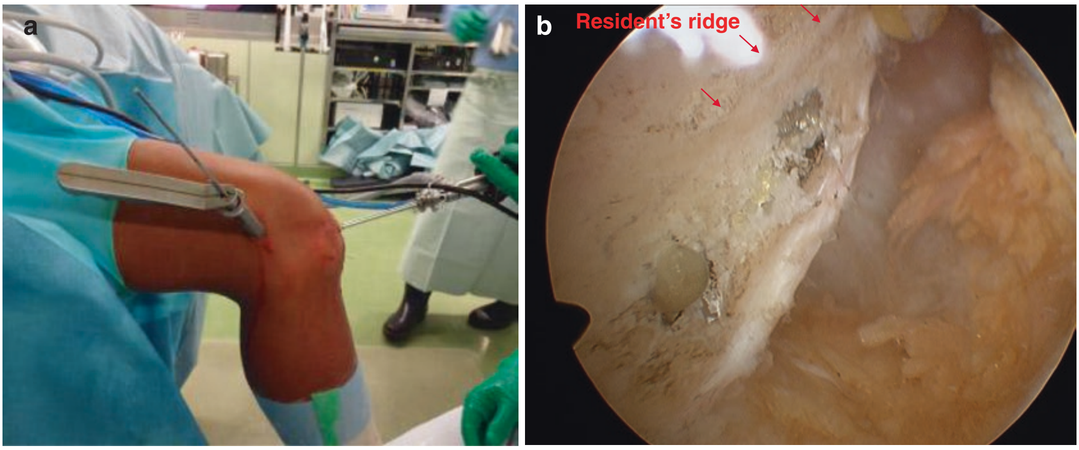

Fig. 21.6 Rectangular femoral tunnel creation in outside-in fashion. (**a**) A 11-mm skin protection cannula is installed over the guide pin via 2-cm lateral femoral incision. (**b**) Two guide pins are drilled parallel to the central pin along the long axis of the attachment area or the resident's ridge with the aid of a 10-mm in-line offset drill guide

resident's ridge that forms an angle of 30° to the femoral axis (Fig. 21.6b). After the central pin is removed, two guide pins are over-drilled with 5-mm drill-bit. With the dilator of 5 × 10 mm *(Smith&Nehew, # E0014050-2)* from the lateral femoral cortex, the two drill holes are dilated into one rectangular tunnel in outside-in fashion [4, 5] (Fig. 21.7).

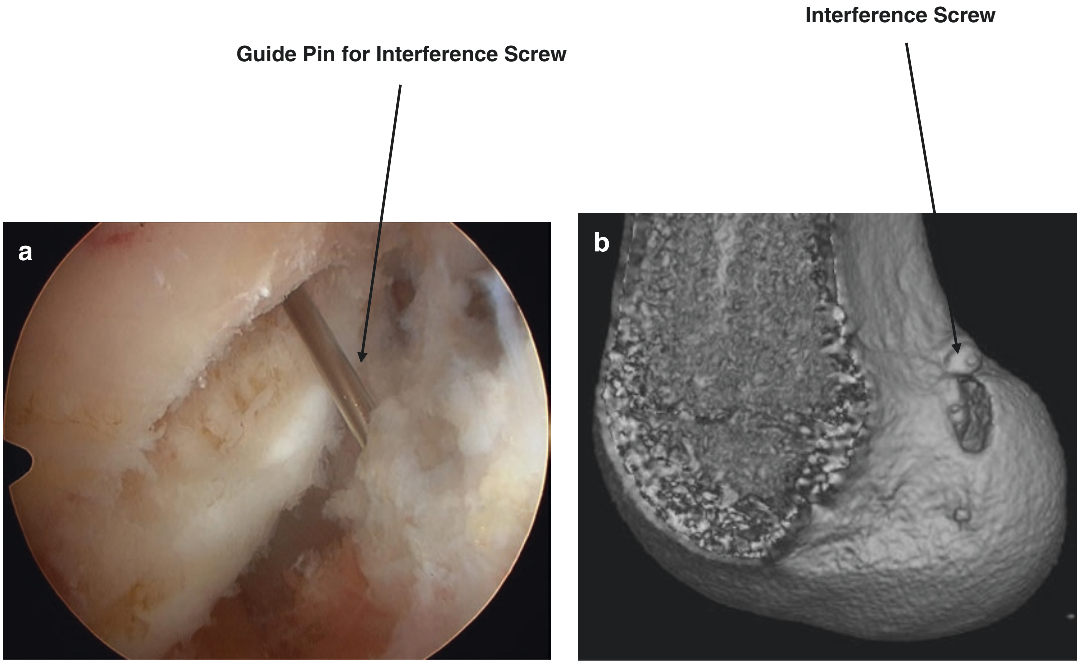

Fig. 21.7 Created rectangular tunnel aperture inside the femoral attachment area. (**a**) Arthroscopic view through the anteromedial portal. (**b**) 3-D CT view

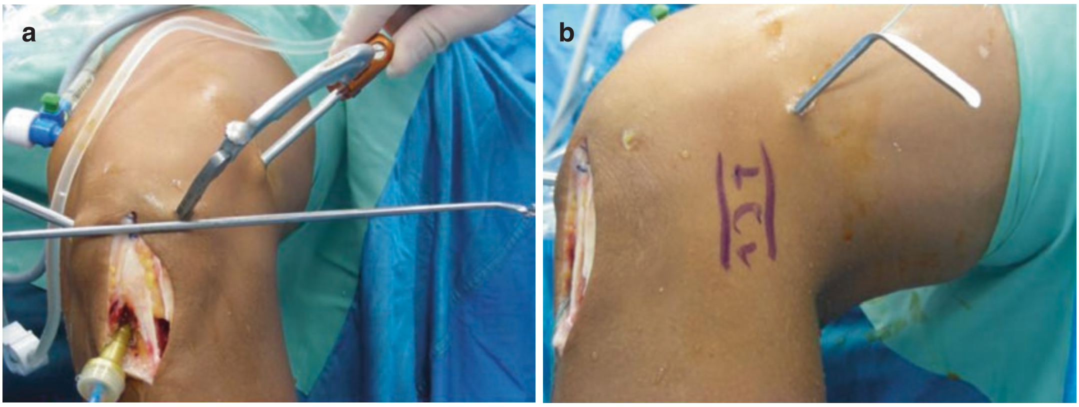

Fig. 21.8 Use of using PIN POINT Guide (S&N Corporation, Andover, MA, USA) for outside-in femoral tunnel creation. Created rectangular tunnel aperture inside the femoral attachment area. (**a**) PIN POINT Guide is introduced through the AL portal. (**b**) Extrarticulary, a 1 cm incision is performed on the lateral thigh, posteriorly to LCL, keeping the guide 20–30° elevated from a plane passing on the transcondylar axis

21.4.2 Round Tunnel (LAP)

The femoral tunnel is drilled from outside to inside using PIN POINT Guide (S&N Corporation, Andover, MA, USA), positioned in the notch, 5 mm posterior to the resident's ridge and 3 mm anterior to the shallow cartilage. Extrarticularly, a 1 cm incision is performed on the lateral thigh, posteriorly to LCL, keeping the guide 20–30° elevated from a plane passing on the transcondylar axis (Fig. 21.8a, b). Based on the PIN POINT Guide, we routinely drilled 8–10 mm tunnel at the time of using patellar BTB. The drill diameter is suggested by the

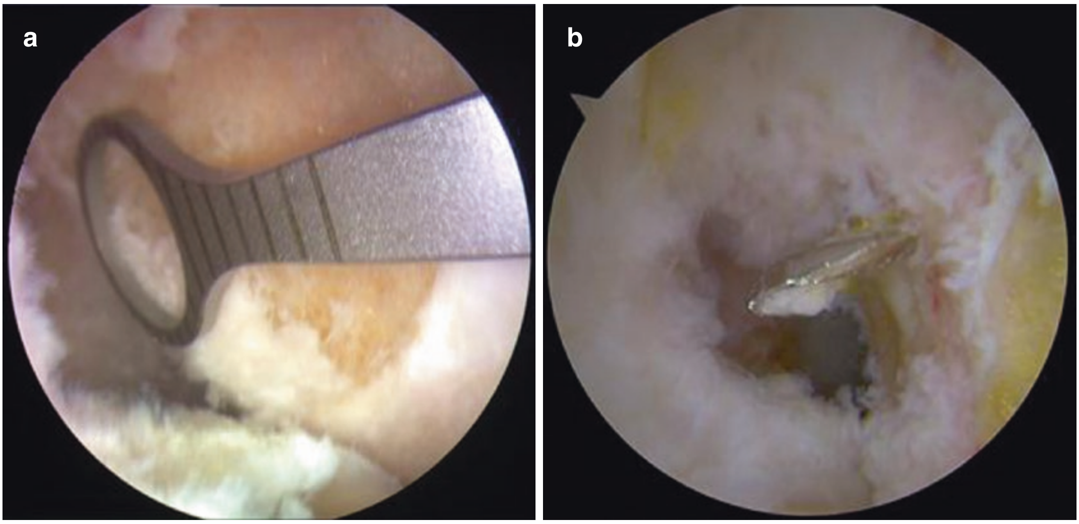

Fig. 21.9 The guide tip and the pin inside the joint. (**a**) The circled guide tip in the right position; (**b**) The guide pin in the right position

dimension of insertional area calculated by the circled guide (7, 8, 9, 10 mm circled guide available) (Fig. 21.9a, b).

References

1. Iwahashi T, Shino K, Nakata K, Otsubo H, Suzuki T, Amano H, Nakamura N (2010) Direct ACL insertion to the femur assessed by histology and three-dimensional volume-rendered computed tomography. Arthroscopy 26:S13–S20
2. Purnell ML, Larson AI, Clancy WG (2008) Anterior cruciate ligament insertions on the tibia and femur and their relationships to critical bony landmarks using high-resolution volume-rendering computed tomography. Am J Sports Med 36(11):2083–2090
3. Hutchinson MR, Ash SA (2003) Resident's ridge assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthroscopy 19:931–935
4. Shino K, Nakata K, Nakamura N, Toritsuka Y, Nakagawa S, Horibe S (2005) Anatomically-oriented ACL reconstruction with a bone-patellar tendon graft via rectangular socket/tunnels: a snug-fit and impingement-free grafting technique. Arthroscopy 21:1402.e1–1402.e5
5. Shino K, Nakata K, Horibe S, Nakamura N, Toritsuka Y, Nakagawa S, Suzuki T (2008) Rectangular tunnel double-bundle anterior cruciate ligament reconstruction with bone–patellar tendon–bone graft to mimic natural fiber arrangement. Arthroscopy 24:1178–1183
6. Shino K, Nakata K, Nakamura N, Mae T, Ohtsubo H, Iwahashi T, Nakagawa S (2005) Anatomic ACL reconstruction using two double-looped hamstring tendon grafts via twin femoral and triple tibial tunnels. Oper Tech Orthop 15:130–134
7. Otsubo H, Shino K, Suzuki D, Suzuki T, Kamiya T, Watanabe K, Fujimiya M, Iwahashi T, Yamashita T (2012) The arrangement and the attachment areas of three ACL bundles. Knee Surg Sports Traumatol Arthrosc 20:127–134
8. Shino K, Horibe S, Hamada M, Nakamura N, Nakata K, Mae T, Toritsuka Y (2002) Allograft anterior cruciate ligament reconstruction. Tech Knee Surg 1:78–85
9. Shino K, Suzuki T, Iwahashi T, Mae T, Nakata K, Nakamura N, Nakagawa S (2010) The resident's ridge as an arthroscopic landmark for anatomical femoral tunnel drilling in ACL reconstruction. Knee Surg Sports Traumatol Arthosc 9:1164–1168

Transtibial Technique

22

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22.1 Introduction

Appropriate femoral tunnel creation at an anatomic position is critical to successfully restore normal knee function after anterior cruciate ligament (ACL) reconstruction [17, 27, 48]. Namely, the femoral tunnel having an appropriate length must be created at an appropriate location and direction in the lateral femoral condyle, avoiding tunnel wall breakage, nerve injuries, and troubles in graft fixation. The femoral tunnel creation techniques are classified into three types, transtibial (TT) technique, anteromedial portal (AMP) technique, and outside-in (OI) technique, according to the approach into the joint cavity. It is important to recognize that, in each technique, a surgeon must make sufficient effort with various ideas and techniques, including location and direction of the tibial tunnel, location of the portal, intraoperative leg position of the patient, forces exerted to the tibia by a surgeon, development of useful guide instruments, etc., to create the appropriate femoral tunnel [38]. For example, in the AMP technique, a surgeon must manually flex the patient's knee as much as possible during creation of the femoral tunnel to avoid breakage of the femoral tunnel wall and damage to the peroneal nerve [38]. In addition, the surgeon must invent various techniques to solve some problems that occur due to the knee flexion position, as described in the Discussion section. In the OI technique, a surgeon must make effort to develop a useful guide to precisely insert a guidewire, to lessen the degree of surgical invasion to the quadriceps muscle, and to reduce graft abrasion at the rough intra-articular edges of the tunnel [38].

The TT technique, in which a femoral tunnel is created through a tibial tunnel, has a relatively long history, and it has been widely carried out in the clinical field. In traditional TT techniques, however, the femoral tunnel was created in a position that was more anterior and superior to the native femoral attachment of the ACL, resulting in vertical graft placement that led to residual rotational laxity [1, 27, 42]. Therefore, many laboratory studies reported that the anatomic femoral tunnel could not be created with the TT technique [8, 37, 41, 44]. However, we should note that these studies evaluated only traditional TT techniques, in which surgeons did not make sufficient effort using useful

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procedures to create the anatomic femoral tunnel in the TT technique. Recently, several studies demonstrated that the anatomical tunnels for single-bundle (SB) and double-bundle (DB) ACL reconstructions could be successfully created with the "modified" TT procedures including some devices. For instance, Yasuda and his colleagues [16, 18, 19, 47] reported that the anatomical femoral tunnels could be created with the modified TT technique in anatomic DB reconstruction. They safely created two relatively thin tibial tunnels, the axis of which passed through the center of the femoral attachment of the anteromedial (AM) and posterolateral (PL) bundles, respectively. They also emphasized that the leg position of the patient, such as the "leg-hanging" and "figure 4" positions, was additionally critical to successfully perform this modified TT technique. Recently, Lee et al. [25] also reported that anatomic SB ACL reconstruction could be successfully performed with the use of their modified TT technique, in which an anterior drawer force, a varus force, and an external rotation force are applied to the proximal aspect of the tibia. They also recommended that an offset guide should be externally rotated for a guidewire insertion. Therefore, these facts suggest that the clinical utility of the TT technique should be reevaluated, taking the recent progression into account.

We believe that it is important for orthopedic surgeons to precisely understand the essence of the TT technique in order to make further progression in the ACL reconstruction hereafter. In this chapter, we first review the history of biomechanical and clinical evaluation studies of the TT technique for SB and DB reconstructions, specifically in comparison with the AMP technique. Second, we explain about the necessity of reevaluation on the utility of the modern TT techniques and that a fundamental problem exists in reevaluating the TT technique in comparison with the AMP and OI techniques. Third, we summarize the essence of the TT technique and the theory of the anatomic femoral tunnel creation and introduce practical TT techniques for anatomic single-bundle (SB) and double-bundle (DB) ACL reconstructions, respectively.

22.2 History of Evaluation Studies of the TT Technique

22.2.1 Biomechanical Evaluations of the TT Technique in SB Reconstruction

To our knowledge, Beck and his colleagues [2] first described an article on the TT technique in 1992. Harner [11] described that there were no significant differences between the TT and OI techniques in the clinical and radiological evaluations, while the TT technique was superior concerning the surgical invasion and the cosmesis. In this technique, femoral tunnels were created at the high-noon orientation through a tibial tunnel created vertically, because a concept of anatomic ACL reconstruction did not exist in those days. Howell et al. [14] modified the TT technique so that an intra-articular outlet of the tibial tunnel was created at the posterior part of the tibial ACL footprint in order to avoid the notch impingement of the graft. They also emphasized the importance of a horizontal tibial tunnel in the coronal plane to achieve graft obliquity [15]. It was easy to create a femoral tunnel at such targeted points through a thick (approximately 10-mm) tibial tunnel. Therefore, these TT techniques were widely performed in the clinical field. However, because the tunnel outlet locations in these techniques were not anatomical, the reconstructed ACL could not sufficiently constrain the rotatory laxity [27, 45].

In 2004, Yasuda et al. [47] reported the first practical "anatomic DB reconstruction" procedure, which anatomically reconstructs both the AM and PL bundles of the ACL, using the TT technique. In this procedure, two femoral tunnels were created at the center of the mid-substance fiber attachments of the AM and PL bundles, respectively. This surgical theory significantly affected the femoral and tibial tunnel locations in the SB procedure, and a concept of "anatomic SB reconstruction," in which the tibial and femoral tunnels were placed at the center to their respective tibial and femoral ACL footprints, was investigated by several cadaveric studies [12, 13, 39]. Then, many studies were conducted to evaluate whether the appropriate femoral tunnel for anatomic SB ACL reconstruction could be accurately created with the TT technique. For example, Heming et al. [12] reported a descriptive laboratory study with cadaveric knees in 2007. They secured the knee in 70° and 90° of flexion and drilled a guide pin from the central femoral ACL attachment site through the central tibial ACL attachment site to the anterior aspect of the tibia. They concluded that the TT technique could produce tunnels centered in the ACL footprints, but a starting point close to the tibial joint line was required. This important fact shows a major part of the essence of the TT technique. Hereafter, several laboratory studies have reported that the anatomic femoral tunnel could be created with the TT technique using a commercially available 7-mm offset guide inserted through a 10- to 11-mm tibial tunnel that was created from the point just anterior to the medial collateral ligament [29, 34, 39], although there was a controversy [42]. These cadaveric studies showed that it is possible to create the anatomical femoral tunnel with the TT technique if the prepared tibial tunnel is appropriately created. However, these studies also pointed out that such horizontal tibial tunnels might lead to other problems, such as a shorter tibial tunnel and an intra-articular elliptical aperture of the tibial tunnel [4, 12]. Therefore, surgeons must invent additional procedures to avoid these problems, as similarly made in the AMP technique.

Then in the 2010s, the AMP technique attracted great notice, and many laboratory studies were conducted to compare the accuracy of the femoral tunnel creation between the traditional TT technique and the AMP technique. Bedi et al. [3] compared the obliquity and length of femoral tunnels between the TT technique, which was performed using the 6-mm offset guide inserted through the laterally created 10-mm tibial tunnel, and the AMP technique performed using the same offset guide at various knee flexion angles. They reported that the AMP technique allowed for slightly greater femoral tunnel obliquity compared with the TT technique, but that there was a substantially increased risk of critically short tunnels and posterior tunnel wall blowout in the AMP technique. Hereafter, many laboratory studies reported similar results, while they concluded that it was impossible to create the anatomical femoral tunnel using the TT technique, while it was possible with the AMP technique [8, 36, 41, 44]. However, we should note that, in the traditional TT techniques evaluated in these studies, a femoral tunnel was instrumentally created using a commercially available 7- to 7.5-mm offset guide inserted through an 8-mm tibial tunnel created with a conventional tibial tunnel guide. Namely, in the traditional TT techniques, surgeons did not make a sufficient effort to create the anatomic femoral tunnel with some useful additional procedures, although such an effort was made in the compared AMP technique. As described above, the previous studies simply concluded that it was impossible to create the anatomical femoral tunnel with the TT technique. However, the conclusion is considered to be logically incorrect, because some useful additional procedures may make it possible. Actually, Lee et al.[25] demonstrated that anatomic single-bundle ACL reconstruction could be accurately performed with the use of the “modified” TT technique, in which they applied an anterior drawer force, a varus force, and an external rotation force to the proximal aspect of the tibia and externally rotated an offset guide. However, scientific studies to compare such “modified” TT techniques with the AMP or OI technique have not been conducted as of yet.

Concerning the postoperative knee stability after the TT and AMP techniques, there has been a controversy. Bedi et al. [4] described that the AMP technique controlled tibial translation significantly more than the TT technique, in which a 6-mm femoral tunnel was created at the center of the ACL footprint through the laterally created 10-mm tibial tunnel. On the other hand, Sim et al. [41] reported that ACL reconstructions performed by the TT, AMP, and OI techniques were biomechanically comparable with each other in restoring normal knee joint laxity and in situ ACL forces and that technical perils and pearls should be carefully considered before choosing a tunnel creating technique.

22.2.2 Clinical Evaluations of the TT Technique in SB Reconstruction

A meta-analysis and meta-regression study reported by Riboh et al. [36] showed that there were no significant differences in the clinical results and failure rates among the three groups. This current evidence shows that the TT, AMP, and OI techniques have equivalent clinical outcomes at short-term to midterm follow-up.

Concerning the graft failure rate after ACL reconstruction, some clinical studies have compared the TT technique with the AMP techniques. In a MOON group study [6], 229 ACL reconstructions with the TT technique were compared with 209 ACL reconstructions with the AMP technique. There was no difference in the revision rate. However, the Danish ACL Reconstruction Registry [35] has shown a lower failure rate for patients who underwent anatomic ACL reconstruction with the TT technique. Namely, in 9,239 patients followed for 4 years, the revision rate for the AMP group was 5.2 % and 3.2 % in the TT group. Recent unpublished data from the Danish ACL Reconstruction Registry have demonstrated that the initial increase in revision rate found when anatomic ACL reconstruction techniques were introduced has improved. However, the TT technique continues to demonstrate a decreased revision rate compared with recent anatomic ACL reconstructions with the AMP technique.

Recently, Clatworthy et al. [5] reported a prospective sequential single-surgeon study. He compared the revision rate between 1,016 hamstring ACL reconstructions with the TT technique (followed for 6–15 years) and 464 ACL reconstructions with AMP technique (followed for 2–6 years). His TT technique utilized a short oblique tibial tunnel which enabled the femoral tunnel to sit within the anatomical footprint in a high AM position. Then, he changed to an AMP technique to enable a central femoral tunnel. This resulted in a more forward (distal) and lower (posterior) femoral tunnel position. Sex, age, graft size, time to surgery, meniscal repair, and meniscectomy data were collected and evaluated as contributing factors for ACL graft failure to enable a multivariate analysis. His revision rate was 5.1 % (52 revisions) in 1,016 ACL reconstructions with the TT technique and 6.9 % (32 revisions) in 464 ACL reconstructions with the AMP technique. Utilizing a single-variate analysis, the AMP technique had a hazard ratio which was significantly higher (2.4×) than the TT technique ($p < 0.001$). There was no difference in sex, age, or lateral meniscal repair rates between the two groups. There were differences in graft size, time to surgery, medial meniscal repair rates, and medial and lateral % meniscus remaining. Adjusting for all these factors, the multivariate hazard ratio was significantly higher (2.3×) for the AMP technique ($p < 0.001$). The AMP technique group had a shorter follow-up period. Therefore, the revision rate was also determined per 100 graft years to determine the relative risk of failure between the two techniques. The revision rate in the AMP technique group was 0.14 failures per 100 graft years, while that in the TT technique group was 0.04 failures per 100 graft years. Thus, the ACL grafts placed more centrally in the footprint had a significantly higher (3.5×) revision rate than the grafts placed in a high AM position per 100 graft years ($p < 0.001$). In the AMP technique group, 61 % of the graft failures occurred in the first year post surgery. In the TT technique group, 27 % of the graft failures occurred in the first year. The failure rate in the early period after ACL reconstruction was significantly higher ($p < 0.001$) in the AMP technique group than in the TT technique group. Thus, he concluded that placement of the ACL graft in a more central femoral footprint position had a higher and earlier revision rate than an ACL graft placed in a high femoral AM position. As will be discussed later in this chapter, the central footprint ACL reconstruction is less isometric. The resultant higher graft strains with central femoral footprint placement are the likely explanation for the increased revision rate.

22.2.3 Evaluations of the TT Technique in DB Reconstruction

Yasuda et al. [47] reported the first practical arthroscopic procedure to anatomically reconstruct the mid-substance fibers of the anteromedial (AM) and posterolateral (PL) bundles of the ACL in 2004 and introduced the TT technique to create two femoral tunnels at the center of the mid-substance fiber attachments of the AM and PL bundles, respectively. To successfully perform this TT technique, they developed two special procedures [16, 21, 51]. One procedure was concerning tibial tunnel placement. Namely, they created relatively thin, horizontal, and lateral tunnels in the tibia using a specially designed guide. The other procedure was concerning utilization of the physiological knee laxity. They performed the TT technique in the "leg-hanging" or "figure 4" positions, which could apply distraction, varus, and internally rotatory forces to the tibia. Then, a number of clinical studies have been conducted to evaluate the clinical utility of the anatomic DB reconstruction. In these studies having Evidence Level I or II, the TT technique was used in almost all AM bundle reconstructions and in half of the PL bundle reconstructions [50]. These facts show that the TT technique has been successfully used for anatomic DB ACL reconstruction. However, Giron et al. [9] reported that all TT techniques cannot be successfully applied to the anatomical femoral tunnel creation. They described that they could not insert femoral wires at the anatomical positions with their TT technique, in which the tibial AM and PL tunnels were created with Howell's guide and a specially designed device attached to this guide, respectively.

There were only a few studies to compare the TT technique with the AMP technique in anatomic DB reconstruction. A laboratory study by Otani et al. [33] showed that a guide-wire could be anatomically drilled through either the tibial AM or PL bundle insertion site to either the femoral AM or PL insertion site. They also pointed out that the AMP technique had a higher risk of peroneal nerve injury in comparison to the TT technique and that it should be undertaken carefully at a higher knee flexion angle in order to avoid this risk. On the other hand, two clinical studies [28, 43] concluded that the TT technique was less accurate in terms of creating the anatomic femoral tunnels than the AMP and OI techniques. In these studies, however, the researchers did not clarify whether their targeted points for the femoral tunnel were really anatomical, although they cited some previous numerical data. We should recognize that there have been controversies concerning the anatomical femoral tunnel location to date, as will be explained later. The accuracy on tunnel creation with each technique is calculated from the difference between a created tunnel and a targeted point. Therefore, if their targeted points on the femur would not be anatomical, the reversed conclusion might be obtained from the same results. Therefore, it is urgently required to decide where the most appropriate tunnel location is on the femoral condyle in order not only to reevaluate the previous conclusions but also to conduct new comparative studies.

Additionally, a clinical study by Nakamae et al. [32] reported that both the TT and AMP techniques were clinically effective in terms of restoration of joint stability and knee scores, although femoral tunnel length in the AMP technique was shorter and position of the EndoButton was more infero-posterior than that in the TT technique.

22.3 Necessity of Reevaluation on the Utility of the TT Technique

22.3.1 Criticism to the Previous Evaluation of the TT Technique

From the logical viewpoint, there are three principles to conduct a scientific study to compare the clinical utility of the TT, AMP, and OI techniques. Firstly, before starting a comparative study, researchers should clearly define the most appropriate point for the femoral tunnel creation, and this point must be recognized as only one targeted point in each technique. Secondly, in each technique, a surgeon must make sufficient effort to insert a guidewire at this targeted point in the femoral tunnel creation, using some useful procedures. Thirdly, researchers should select the most useful modified technique in the TT, AMP, or OI technique and compare those representative techniques concerning not only the accuracy but also the merits and demerits of each technique.

Based on these principles, we should verify whether the conclusions given in the previous comparative studies were logically appropriate. In those studies, firstly, researchers did not clearly decide only one targeted point for each femoral tunnel creation, before starting the comparative studies. Specifically in their TT techniques, the surgeons did not intentionally aim a guidewire at the targeted point. Secondly, the surgeons must make sufficient effort to insert a guidewire at this targeted point in the TT technique, although such effort was made in the AMP and OI techniques. Thirdly, the researchers did not compare the most useful TT technique with the AMP and OI techniques, because they used the conventional TT techniques. These are logical flaws in the previous conclusions. Therefore, we have to say that the conclusions given in the previous comparative studies were not logically appropriate. Currently, the TT technique has been much improved, as described below [25, 47]. Therefore, it is necessary to conduct new comparative studies to reevaluate the utility of the modern TT technique, based on the above-described three principles.

22.3.2 Fundamental Problem in Conducting New Comparative Evaluation Studies

To conduct a new comparative study, however, we should recognize that there has been a fundamental problem concerning the first principle that the most appropriate point to create a femoral tunnel outlet must be definitely decided before starting a comparative study, although a number of anatomical and biomechanical studies have investigated about this issue. Namely, in the clinical field, there have been controversies about an answer to the following question: where are femoral tunnel outlets created in anatomic SB and DB ACL reconstructions? For example, in the field of SB reconstruction, many studies recommended that a femoral tunnel outlet should be created at the center of the direct attachment of the ACL mid-substance fibers [12, 13, 39]. However, some other studies reported that a femoral tunnel outlet should be created at the center of the direct attachment of the mid-substance fibers of the PL bundle [46] or at the center of the fanlike extension fiber attachment on the most posterior part of the lateral condyle [40]. Regarding DB reconstruction, there are also some controversies. Yasuda and his colleagues [23, 47–49] recommended to create two femoral tunnels at the center of the direct attachment of the AM and PL bundle mid-substance fibers, based on the basic studies [18, 20, 31]. On the other hand, some other studies reported to create an AM tunnel in the fanlike extension fiber attachment [7, 28, 43]. Which is the most appropriate tunnel location for SB or DB reconstruction? The answer to this question will directly affect the decision that the accuracy of the TT technique is inferior or superior to that of another technique, because the decision on the accuracy of the tunnel creation will be made by measuring the difference between the most appropriate tunnel location and the created tunnels. Therefore, it is urgently required for future studies to decide where the most appropriate tunnel location is on the femoral condyle.

22.4 Useful TT Techniques for Anatomic SB and DB Reconstructions

22.4.1 Essence of the TT Technique

To reevaluate the utility of the TT technique in comparison with the other two techniques, we summarize about the essence of the TT technique. The above-described history has shown that the TT technique does not mean a simple technique in which a surgeon creates a femoral tunnel through a tibial tunnel created independently to the femoral tunnel. The TT technique is a technique to create the anatomical femoral tunnel through a tibial tunnel using two types of special procedures performed by a surgeon. First, a surgeon must create a tibial tunnel that goes to the most appropriate point to create an anatomical femoral tunnel [51]. Such a tibial tunnel becomes more horizontal than a conventional tunnel [12]. Secondly, the surgeon should apply an adequate amount of distraction, varus, and rotatory forces to the tibia to utilize the physiological knee laxity in the femoral tunnel creation through such a tibial tunnel [16, 25, 47, 51]. It should be emphasized that these special procedures should be complementarily performed. For instance, if a surgeon creates a 7-mm tibial tunnel that accurately goes to the most appropriate point to create an anatomical femoral tunnel in anatomic PL bundle reconstruction, this tibial tunnel may have a risk of joint surface destruction in the tibia. In such cases, the surgeon must create the tibial tunnel more vertically to avoid the joint surface destruction. However, the TT technique can be successfully performed by using the “figure 4” position of the knee, in which varus and internally rotatory forces are applied to the knee. Also in anatomic SB reconstruction, because an oblique10-mm tibial tunnel may lead to other problems, such as a shorter tunnel and widening of the intra-articular aperture [4, 12], Lee et al. [25] successfully performed the TT technique through a relatively vertical tibial tunnel by applying an anterior drawer force, a varus force, and an external rotation force to the proximal aspect of the tibia and externally rotating an offset guide used for a guidewire insertion. These facts show that the combined effect from the two special procedures is essential to lead the TT technique to success.

22.4.2 Theory on the Anatomic Femoral Tunnel Creation

Where should each tunnel be created on the femoral condyle in anatomic SB and DB ACL reconstructions? It is essential to answer this question in order to evaluate each technique. However, there have been some controversies on the answer, as described above. Therefore, we must first explain about the theory of our anatomic femoral tunnel creation, before introducing useful TT techniques for SB and DB reconstructions. The broad femoral attachment of the ACL is composed of the direct attachment of the mid-substance fibers and the fanlike extension fibers [30]. The former is relatively narrow and long, with its long axis inclined toward the posterior direction by 30° to the long axis of the femur [10, 26, 47]. The latter fibers extend from the mid-substance fibers and broadly spread out on the posterior condyle. Recently, we found out that a deep fold is formed at the border between the mid-substance and the fanlike extension fibers during knee flexion [31] (Fig. 22.1). This fact suggested that a force from the ACL mid-substance might not be distributed to the fanlike extension fibers over this fold. Most recently, our biomechanical study demonstrated that, in anterior tibial displacement, the attachment of the mid-substance fibers resisted 82–90 % of the anterior drawer force, while the fanlike extension fibers contributed very little [20] (Fig. 22.2). These facts suggest that it is of less value to reconstruct the fanlike extension fibers in ACL reconstruction. Based on the anatomical and biomechanical knowledge, we can confirm that what should be “anatomically” reconstructed in the anatomic SB and DB ACL reconstructions is not the whole structure of the ACL including the fanlike extension fibers but the mid-substance fibers of the ACL or the AM and PL bundles including the direct attachment. Therefore, in anatomic SB reconstruction, we should create a femoral tunnel at the center of the direct attachment of the ACL mid-substance fibers. Also in anatomic DB reconstruction, two femoral tunnels should be created at the center of the direct attachment of the AM and PL mid-substance fibers, respectively.

22.4.3 A Useful TT Technique for Anatomic SB Reconstruction

Lee et al. [25] reported a useful TT technique for SB reconstruction. In creating the tibial tunnel, the knee was flexed to 90°, and the entry point was set 4–5 cm distal to the joint line, 2–3 cm

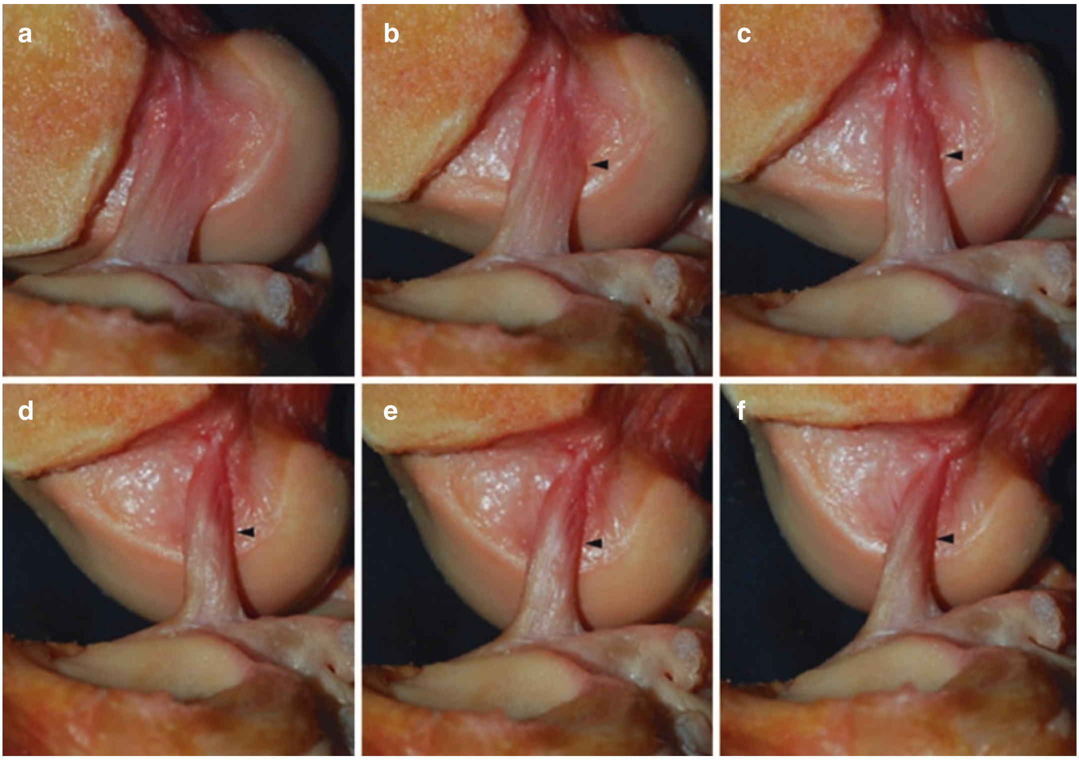

Fig. 22.1 Dynamic observation of the mid-substance and fanlike extension fibers during flexion-extension motion of the knee. At 15–30° of flexion (**b**, **c**), the mid-substance fibers were found to slightly curve (*black arrowhead*) approximately at the postero-proximal edge of the direct attachment of the mid-substance fibers. At 45° (**d**), the curving of the ACL fibers was an obvious fold. At 60° (**e**), the mid-substance fibers started to become twisted, and the fold became deep specifically at the postero-distal portion (From [31] with permission)

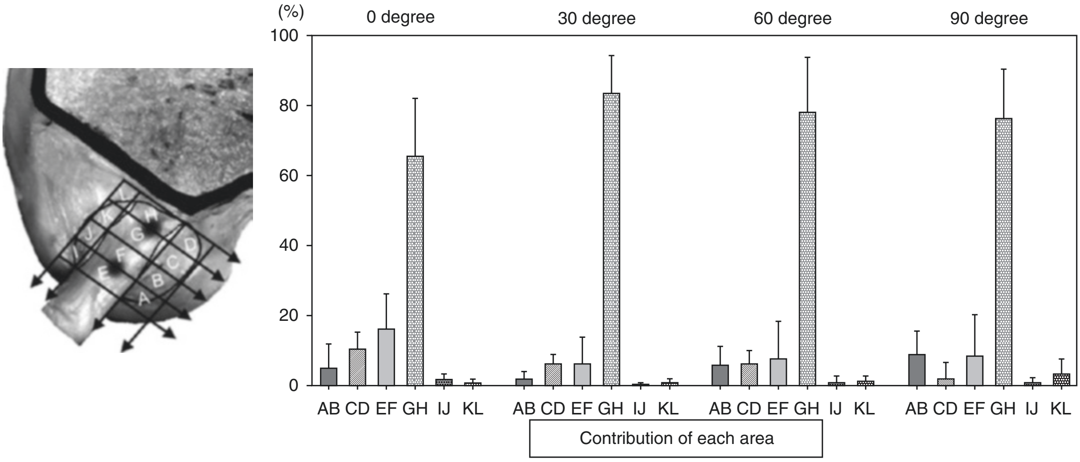

Fig. 22.2 Partition of femoral ACL attachment on lateral wall of intercondylar notch. Areas *A*, *B*, *C*, and *D* comprise the posterior fanlike extension; areas *E*, *F*, *G*, and *H* comprise the central direct attachment area; and areas *I*, *J*, *K*, and *L* comprise the anterior fanlike extension. The percentage contribution of each area to a 6-mm anterior translation of the tibia was calculated, when the force of the anterior cruciate ligament in the intact knee condition was considered 100 %. The mid-substance fibers (*E*, *F*, *G*, and *H*) transmitted 82–90 % of the resistance to tibial displacement, while the fanlike extension fibers contributed only 10–15 % of the resistance (From [20] with permission)

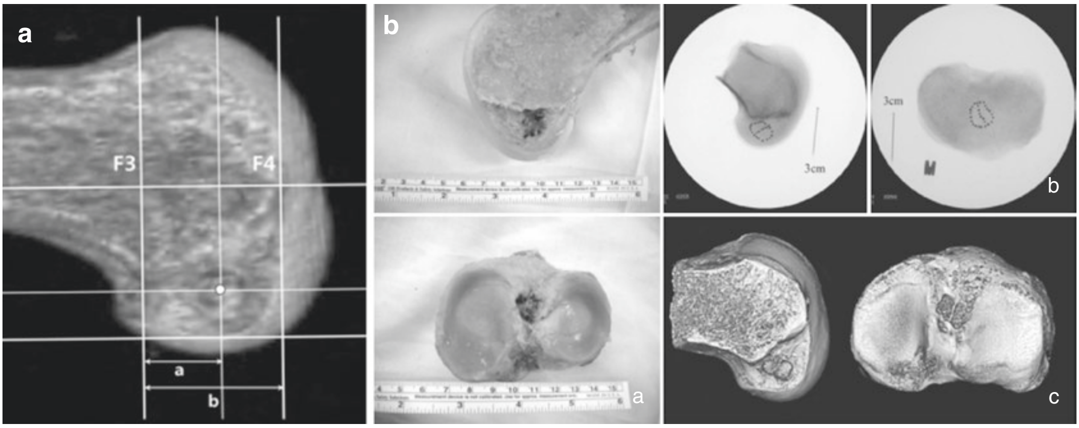

Fig. 22.3 (**a**) A three-dimensional reconstructed CT image of the femoral tunnel aperture created with the modified TT technique (From [25] with permission). (**b**) This femoral tunnel position was identical to the anatomic point, which was shown in the cadaveric study (From [26] with permission)

posteromedial to the tibial tuberosity, 1 cm superior to the attachment site of the pes anserinus, and just anterior to the medial collateral ligament (MCL). A guide pin was then inserted at an angle of 60° to the tibial plateau with the use of a tibial drill guide (Acufex, Andover, Massachusetts) aimed midway between the ACL footprints of the anteromedial and posterolateral bundles. A 10-mm tibial tunnel was drilled. In creating the femoral tunnel, a 7-mm offset femoral drill guide (Acufex) was aimed at the lateral bifurcate ridge on the medial wall of the lateral femoral condyle with the knee flexed to 90° and an anterior drawer force, a varus force, and an external rotation force applied to the proximal aspect of the tibia while externally rotating the guide. The anterior drawer force enables more inferior positioning of the femoral tunnel; the varus force, posterior positioning of the femoral tunnel; and the external rotation force and external rotation of the guide, both inferior positioning and posterior positioning of the femoral tunnel. A femoral tunnel guide pin was then inserted through the guide, and a 10-mm femoral tunnel was drilled through the tibial tunnel.

Lee et al. [25] radiologically and clinically evaluated this TT technique in comparison with the AMP technique. Two- and three-dimensional images of CT scans showed that there were no significant differences concerning not only the graft obliquity in the coronal and sagittal planes but also the femoral tunnel position, as evaluated with the use of the quadrant method, between the two groups (Fig. 22.3a). This femoral tunnel position was identical to the anatomic point (Fig. 22.3b), which was shown in the previous anatomical study [26]. In addition, there were no significant differences in the clinical results between the two groups in terms of manual laxity tests, arthrometric analysis, and several clinical scores.

22.4.4 A Useful TT Technique for Anatomic DB Reconstruction

Yasuda et al. [47] reported the first practical procedure to reconstruct the mid-substance fibers of the AM and PL bundles using the TT technique. To create the tibial tunnels for the PL and AM bundles, they developed an arthroscopy-assisted guidewire navigation device (Guidewire Navigator III, Smith and Nephew Endoscopy Japan, Tokyo, Japan). The surgeon holds the tibia at 90° of knee flexion, keeping the femur horizontal, and placed a tip of this device at the center of each bundle footprint on the tibia (Fig. 22.4). Then, after they aimed the femoral indicator in the tip at the center of each footprint on the femur, the extra-articularly located wire sleeve was fixed on the anteromedial aspect of

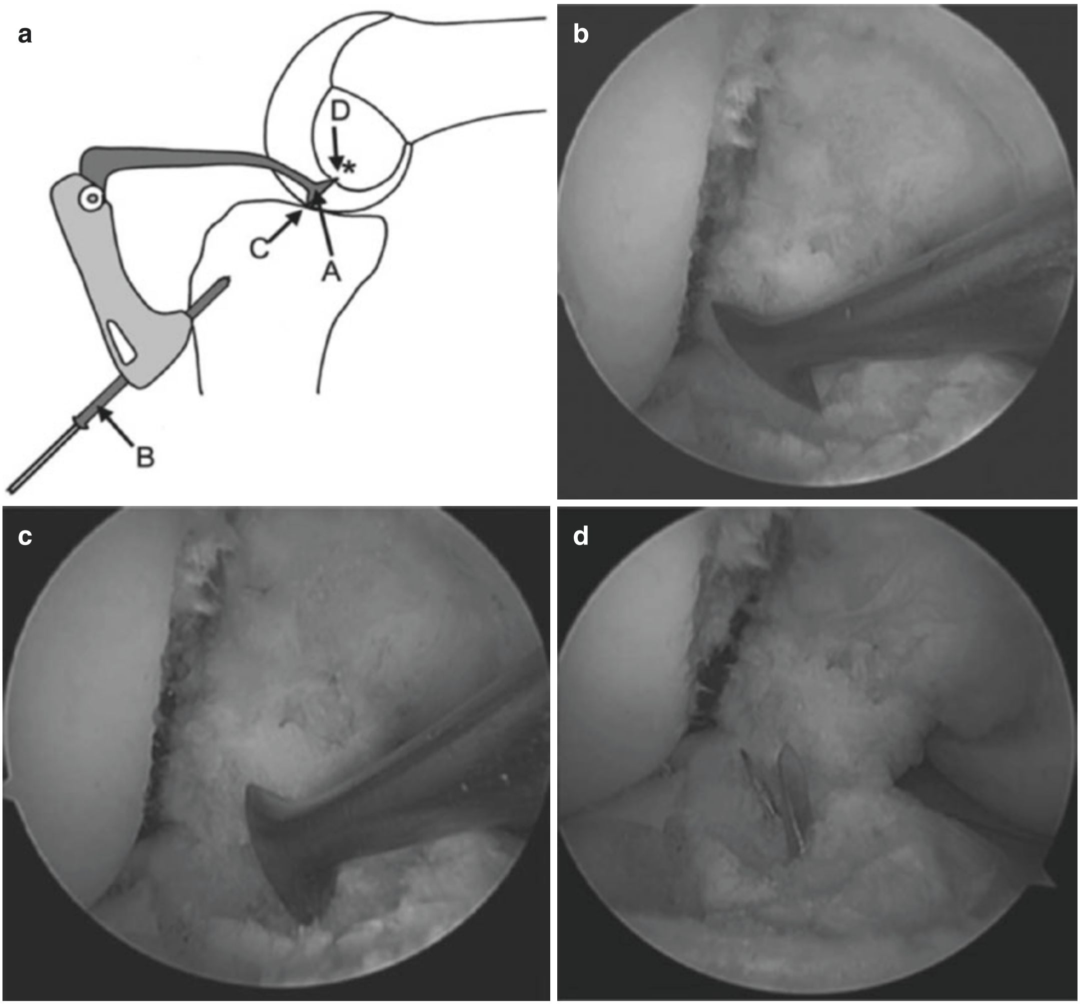

Fig. 22.4 A guidewire navigation device is composed of a Navi-tip (**a**) and a Wire-sleeve (**b**). The Navi-tip consists of a tibial indicator (**c**) and femoral indicator (**d**). The axis of the Wire-sleeve passed through the tip of the tibial indicator. The direction and position of the Wire-sleeve were automatically decided, independent of those of the Navi-tip. (**b**) Placement of the Navi-tip of the Wire-navigator to create the posterolateral bundle. (**c**) Placement of the Navi-tip to create the anteromedial bundle. (**d**) Two Kirschner wires were drilled through the sleeve in the tibia. Note the difference in the direction between the two wires (From [47] with permission)

the tibia. Thus, the location and direction of the wire sleeve were automatically determined on the tibia, depending on the direction of the intra-articular navigator tip. A Kirschner wire of 2 mm in diameter is drilled through the sleeve in the tibia. The first tunnel is made for the PL bundle reconstruction with a cannulated drill which corresponds to the measured diameter of the prepared substitute (commonly 6 mm). Then, the second tunnel is drilled for the AM bundle reconstruction in the same manner (commonly 7 mm). In the patients successfully operated with this TT technique, the tibial tunnel angles of the posterolateral bundle averaged 41° in the anteroposterior view and 35° in the lateral view [21]. The tibial tunnel angles of the anteromedial bundle averaged 16° in the anteroposterior view and 41° in the lateral view.

Concerning the femoral tunnel creation for the AM bundle reconstruction, our anatomical study [18] demonstrated that the averaged center of the direct attachment of the AM bundle mid-

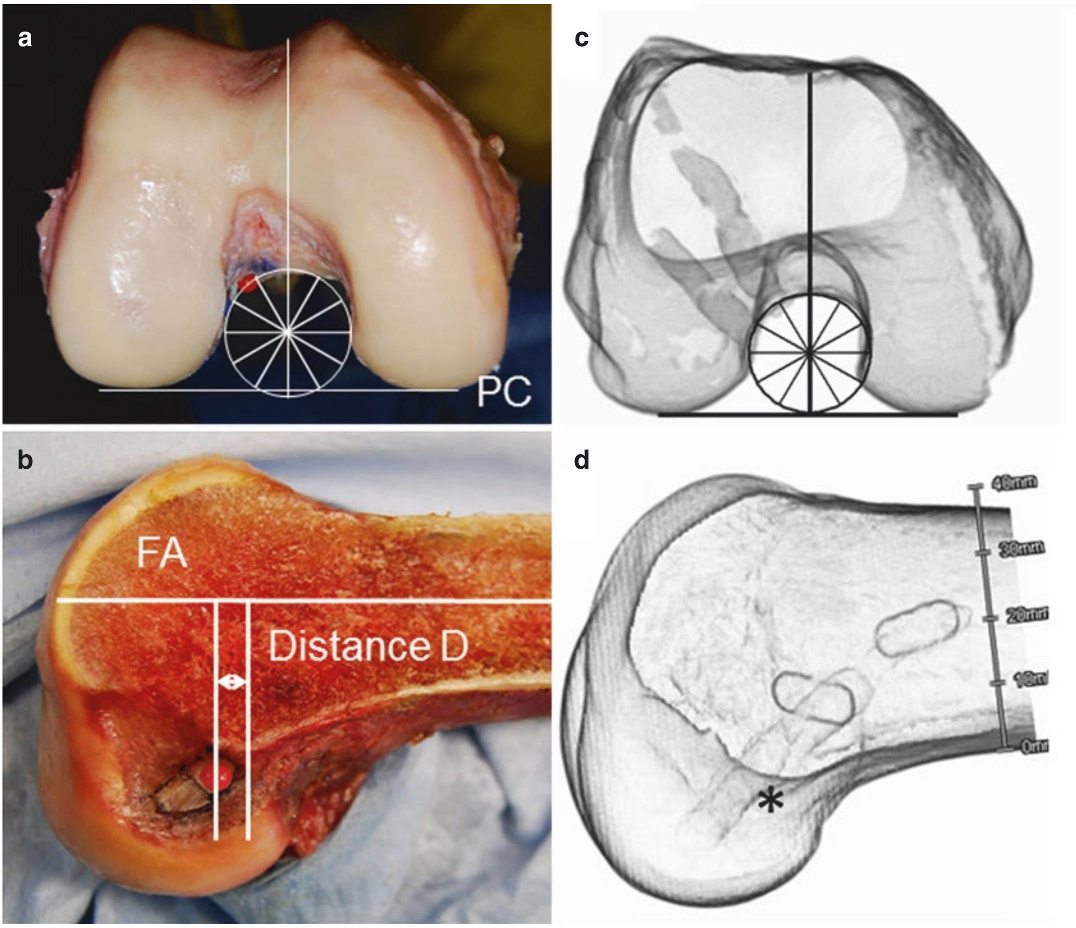

Fig. 22.5 On a photograph taken in the axial view (**a**), the center of the AM bundle attachment (*a red marker*) was measured with the so-called “clock” system. On a photograph taken in the lateral view (**b**), we measured “Distance D” from the POIN. Three-dimensional CT images taken in the axial view (**c**) and the lateral view (**d**) demonstrated that the center of an actually created AM tunnel was identical to the center of the AM bundle attachment (From [18] with permission)

substance fibers was located on the cylindrical surface of the femoral intercondylar notch at “10:37” (or “1:23”) o’clock orientation in the distal view and at 5.0 mm from the proximal outlet of the intercondylar notch (POIN) in the lateral view (Fig. 22.5). To insert a guidewire into this point, we developed the following quantitative method: through the tibial tunnel, we introduced a 5-mm offset guide (Twisted Offset Guide, Smith and Nephew Endoscopy Inc., Tokyo, Japan) into the joint cavity and set the hook-shaped tip of this guide at the POIN at 90–100° of knee flexion. Keeping the hook at this point, we aimed a guidewire at the “1:30” or “10:30” o’clock orientation, an eighth of a circle, in the arthroscopic visual field. Thus, in actual operations, a surgeon inserted a Kirschner wire to the femur using this quantitative technique. Our clinical study [18] to evaluate the accuracy of this technique showed that the average location of the AM tunnel actually created in the ACL reconstruction was at “10:41” (or “1:19”) o’clock orientation and at 5.0 mm from the POIN (Fig. 22.5). There was no significant difference between the averaged center location of the native AMB attachment and that of the actually created tunnels. The results suggested that the above-described quantitative technique is useful to

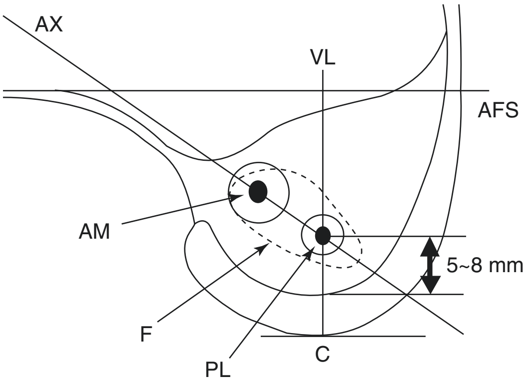

Fig. 22.6 On a schematic picture of the attachment of the mid-substance fibers of the ACL (*dotted line*) drawn at 90° of flexion, we drew a vertical line (*VL*) through the contact point (*C*) between the femoral condyle and the tibial plateau line and a long axis line of the ACL attachment (*AX*). The two lines crossed at the point (*PL*) on the vertical line 5–8 mm anterior to the edge of the joint cartilage. The center of the attachment of the PL bundle was located approximately at this crossing point (From [47] with permission)

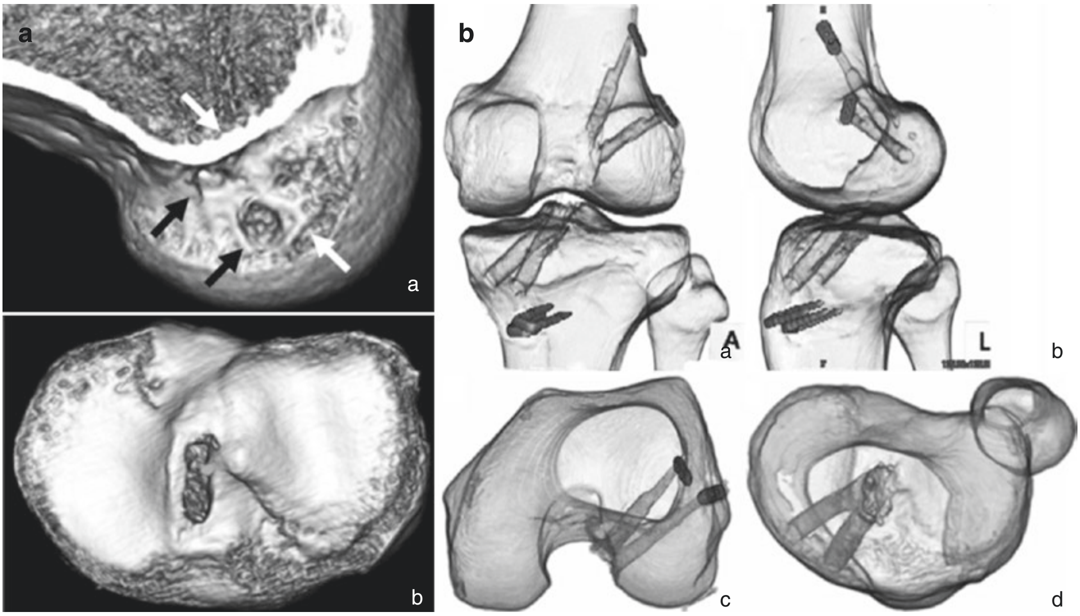

Fig. 22.7 The anatomical femoral tunnel outlets created for anatomic DB reconstruction with the TT technique (**a**) (From [51] with permission). Transparent 3D CT images show that four tunnels were appropriately created with this TT technique (From [16] with permission)

insert a guidewire into the averaged center of the native AM bundle attachment.

Regarding the femoral tunnel creation for the PL bundle reconstruction, we reported a geometric method to estimate the averaged center of the direct attachment of the PL bundle mid-substance in the original procedure [47]. In an arthroscopic visual field, we could draw an imaginary vertical line through the contact point between the lateral femoral condyle and the tibial plateau at 90° of knee flexion. This line and the long axis of the ACL remnant were crossed at the point 5–8 mm anterior to the edge of the joint cartilage (Fig. 22.6). The averaged center of the normal attachment of the PL bundle was located approximately at this crossing point. In actual operation, a surgeon observed the lateral condyle with a 30° arthroscope inserted through the medial infrapatellar portal, keeping the femur horizontal at 90° of knee flexion. The surgeon held a guidewire manually and aimed it at the crossing point on the femur through the tibial tunnel. To adjust the guidewire at this point, a surgeon must utilize the physiological knee laxity. Namely, the "leg-hanging" position is commonly necessary, and the "figure 4" position is needed in some cases. Thus, two anatomical femoral tunnels were created on the lateral condyle (Fig. 22.7a).

To evaluate this TT technique, several radiological, biomechanical, and clinical studies have been conducted. Inoue et al. [16] radiologically evaluated the accuracy of this TT technique (Fig. 22.7b) and reported that it is useful for clinical use. Biomechanically, the tunnel positions created with this TT technique could restore the knee functions close to that of the normal knee [23, 49]. The clinical results of this anatomic DB reconstruction procedure are significantly better that the conventional SB reconstruction [22, 48]. In addition, recently, this TT technique has been successfully performed in remnant tissue-preserving anatomic DB reconstruction.

22.5 Discussion

The review has showed that, although the conventional TT techniques had obvious disadvantages, many “modified” TT techniques have recently been reported to improve them. This chapter has explained that the anatomic tunnel creation can be successfully performed with the modern TT techniques in both SB and DB ACL reconstructions, although there are some controversies concerning the anatomic femoral point on the femoral condyle. Then, we should recognize that, not only in the AMP and OI techniques but also in the TT technique, a surgeon must use some additional procedures to precisely or safely insert a guidewire at the anatomical point on the femur. In the future studies to compare the TT technique with the other two techniques, researchers should evaluate not only the accuracy of the tunnel location and direction but also all merits and demerits of the additional procedures.

At this time, the TT, AMP, and OI techniques have their own set of advantages and disadvantages [38]. Concerning the TT technique, the advantages include less surgical pain and morbidity, better cosmesis with no lateral incision, reduced surgical time, parallel bone tunnels, technically familiar and less demanding, lower risk of revision, and beneficial to place the graft penetrating the remnant ACL tissue [24, 51]. The disadvantages involved elliptical tunnel outlet on the lateral condyle, inability to freely position femoral tunnel, fluid leakage through the tibial tunnel, and an increased cost due to special devices [38]. On the other hand, the AMP technique has the following advantages and disadvantages [38]. The advantages include independent placement of femoral and tibial tunnels, ease of approach to the femoral targeted point, tunnel placement independent of tunnel guides, and allowing parallel placement of interference screws. The previous studies pointed out the following disadvantages: technically demanding (difficulty visualizing instruments due to limited visibility in hyperflexion, inability to maintain aimer in hyperflexed knee, difficulty passing instruments due to portal tightening in hyperflexion, difficulty seating endoscopic aimer), challenges with graft fixation device passage, short or bicortical sockets which may limit fixation options, potential damage to common peroneal nerve, posterior-wall blowout and potential damage to posterior articular cartilage, iatrogenic damage to cartilage of medial femoral condyle, low portal placement which may injure anterior horn of medial meniscus, higher graft failure rates, and increased risk of revision. Concerning the OI technique, the following advantages and disadvantages have been described in the previous reports [38]. The advantages include less risk of bone tunnel divergence, ease of approach to the targeted point, avoidance of posterior-wall blowout, and ease of use for revision ACL procedures. The disadvantages involve greater surgical morbidity with lateral incision, greater abrasion of the graft at the intra-articular edges of the tunnel, increased operative time, worse cosmesis, and increased cost due to special devices.

Finally, appropriate femoral tunnel creation at an anatomic position is critical to successfully restore normal knee function after ACL reconstruction [17, 27, 48]. However, there are no simply easy techniques in the TT, AMP, and OI techniques. In each technique, a surgeon must make effort with some special ideas and procedures to create the appropriate femoral tunnel. Therefore, it is important for orthopedic surgeons to understand the essence of the TT, AMP, and OI techniques and to train their skill for each technique, in order for the ACL reconstruction to become a success.

References

1. Arnold MP et al (2001) Single-incision technique misses the anatomical femoral anterior cruciate ligament insertion: a cadaver study. Knee Surg Sports Traumatol Arthrosc 9(4):194–199
2. Beck C et al (1992) Anterior cruciate ligament reconstruction with the endoscopic technique. Oper Tech Orthop 2:86–98
3. Bedi A et al (2010) Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. Arthroscopy 26(3):342–350
4. Bedi A et al (2011) Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: an anatomic and biomechanical evaluation of surgical technique. Arthroscopy 27(3):380–390
5. Clatworthy M et al (2015) Transportal central anatomic ACL reconstruction has a higher revision rate than transtibial high AM ACL reconstruction. Presented in APKASS Congress, 2015
6. Duffee A et al (2013) Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. J Bone Joint Surg Am 95(22):2035–2042
7. Forsythe B et al (2010) The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. J Bone Joint Surg Am 92-A(6):1418–1426
8. Gadikota HR et al (2012) The relationship between femoral tunnels created by the transtibial, anteromedial portal, and outside-in techniques and the anterior cruciate ligament footprint. Am J Sports Med 40(4):882–888
9. Giron F et al (2007) Double-bundle “anatomic” anterior cruciate ligament reconstruction: a cadaveric study of tunnel positioning with a transtibial technique. Arthroscopy 23(1):7–13
10. Hara K et al (2009) Anatomy of normal human anterior cruciate ligament attachments evaluated by divided small bundles. Am J Sports Med 37(12):2386–2391
11. Harner CD et al (1994) Anterior cruciate ligament reconstruction: endoscopic versus two-incision technique. Arthroscopy 10(5):502–512
12. Heming JF et al (2007) Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. Am J Sports Med 35(10):1708–1715
13. Ho JY et al (2009) Equal kinematics between central anatomic single-bundle and double-bundle anterior cruciate ligament reconstructions. Arthroscopy 25(5):464–472
14. Howell SM, Barad SJ (1995) Knee extension and its relationship to the slope of the intercondylar roof. Implications for positioning the tibial tunnel in anterior cruciate ligament reconstructions. Am J Sports Med 23(3):288–294
15. Howell SM et al (2001) The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. Am J Sports Med 29(5):567–574
16. Inoue M et al (2010) Tunnel location in transparent 3-dimentional CT in anatomic double-bundle anterior cruciate ligament reconstruction with the trans-tibial tunnel technique. Knee Surg Sports Traumatol Arthrosc 18(9):1176–1183
17. Jepsen CF et al (2007) Does the position of the femoral tunnel affect the laxity or clinical outcome of the anterior cruciate ligament reconstructed knee? A clinical, prospective, randomized, double-blind study. Arthroscopy 23(12):1326–1333
18. Kai S et al (2013) A quantitative technique to create a femoral tunnel at the averaged center of the anteromedial bundle attachment in anatomic double-bundle anterior cruciate ligament reconstruction. BMC Musculoskelet Disord 14:189. doi:10.1186/1471-2474-14-189
19. Kawaguchi et al (2013) Tunnel enlargement and coalition after anatomic double-bundle anterior cruciate ligament reconstruction with hamstring tendon autografts: a computed tomography study. Orthop J Sports Med 1(1):2325967113486441
20. Kawaguchi Y et al (2015) The role of fibers in the femoral attachment of the anterior cruciate ligament in resisting tibial displacement. Arthroscopy 31(3):435–444
21. Kondo E et al (2007) Radiologic evaluation of femoral and tibial tunnels created with the transtibial tunnel technique for anatomic double-bundle anterior cruciate ligament reconstruction. Arthroscopy 23(8):869–876
22. Kondo E et al (2008) Prospective clinical comparisons of anatomic double-bundle versus single-bundle anterior cruciate ligament reconstruction procedures in 328 consecutive patients. Am J Sports Med 36(9):1675–1687
23. Kondo E et al (2010) Biomechanical comparisons of knee stability after anterior cruciate ligament reconstruction between 2 clinically available transtibial procedures: anatomic double bundle versus single bundle. Am J Sports Med 38(7):1349–1358
24. Kondo E et al (2015) Effects of remnant tissue preservation on clinical and arthroscopic results after anatomic double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 43(8):1882–1892
25. Lee JK et al (2014) Anatomic single-bundle ACL reconstruction is possible with use of the modified transtibial technique: a comparison with the anteromedial transportal technique. J Bone Joint Surg Am 96-A(8):664–672
26. Lee JK et al (2015) Anatomy of the anterior cruciate ligament insertion sites: comparison of plain radiography and three-dimensional computed tomographic imaging to anatomic dissection. Knee Surg Sports Traumatol Arthrosc 23(8):2297–2305
27. Lee MC et al (2007) Vertical femoral tunnel placement results in rotational knee laxity after anterior cruciate ligament reconstruction. Arthroscopy 23(7):771–778

28. Lee YS et al (2012) Comparative analysis of femoral tunnels between outside-in and transtibial double-bundle anterior cruciate ligament reconstruction: a 3-dimensional computed tomography study. Arthroscopy 28(10):1417–1423
29. Miller MD et al (2010) The effects of extra-articular starting point and transtibial femoral drilling on the intra-articular aperture of the tibial tunnel in ACL reconstruction. Am J Sports Med 38(4):707–712
30. Mochizuki T et al (2006) Cadaveric knee observation study for describing anatomic femoral tunnel placement for two-bundle anterior cruciate ligament reconstruction. Arthroscopy 22(4):356–361
31. Mochizuki T et al (2014) Anatomic and histologic analysis of the mid-substance and fan-like extension fibres of the anterior cruciate ligament during knee motion, with special reference to the femoral attachment. Knee Surg Sports Traumatol Arthrosc 22(2):336–344
32. Nakamae A et al (2012) Clinical comparisons between the transtibial technique and the far anteromedial portal technique for posterolateral femoral tunnel drilling in anatomic double-bundle anterior cruciate ligament reconstruction. Arthroscopy 28(5):658–666
33. Otani M et al (2012) Comparative risk of common peroneal nerve injury in far anteromedial portal drilling and transtibial drilling in anatomical double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 20(5):838–843
34. Piasecki DP et al (2011) Anterior cruciate ligament reconstruction: can anatomic femoral placement be achieved with a transtibial technique? Am J Sports Med 39(6):1306–1315
35. Rahr-Wagner L et al (2013) Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. Arthroscopy 29(1):98–105
36. Riboh JC et al (2013) Transtibial versus independent drilling techniques for anterior cruciate ligament reconstruction: a systematic review, meta-analysis, and meta-regression. Am J Sports Med 41(11):2693–2702
37. Robert HE et al (2013) Coverage of the anterior cruciate ligament femoral footprint using 3 different approaches in single-bundle reconstruction: a cadaveric study analyzed by 3-dimensional computed tomography. Am J Sports Med 41(10):2375–2383
38. Robin BN et al (2015) Advantages and disadvantages of transtibial, anteromedial portal, and outside-in femoral tunnel drilling in single-bundle anterior cruciate ligament reconstruction: a systematic review. Arthroscopy 31(7):1412–1417
39. Rue JP et al (2008) Femoral tunnel placement in single-bundle anterior cruciate ligament reconstruction: a cadaveric study relating transtibial lateralized femoral tunnel position to the anteromedial and posterolateral bundle femoral origins of the anterior cruciate ligament. Am J Sports Med 36(1):73–79
40. Shino K et al (2008) Rectangular tunnel double-bundle anterior cruciate ligament reconstruction with bone-patellar tendon-bone graft to mimic natural fiber arrangement. Arthroscopy 24(10):1178–1183
41. Sim JA et al (2011) Biomechanical evaluation of knee joint laxities and graft forces after anterior cruciate ligament reconstruction by anteromedial portal, outside-in, and transtibial techniques. Am J Sports Med 39(12):2604–2610
42. Strauss EJ et al (2011) Can anatomic femoral tunnel placement be achieved using a transtibial technique for hamstring anterior cruciate ligament reconstruction? Am J Sports Med 39(6):1263–1269
43. Takeda Y et al (2013) Comparison of tunnel orientation between transtibial and anteromedial portal techniques for anatomic double-bundle anterior cruciate ligament reconstruction using 3-dimensional computed tomography. Arthroscopy 29(2):195–204
44. Tompkins M et al (2013) Anterior cruciate ligament reconstruction femoral tunnel characteristics using an accessory medial portal versus traditional transtibial drilling. Arthroscopy 29(3):550–555
45. Woo SL et al (2002) The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon. A cadaveric study comparing anterior tibial and rotational loads. J Bone Joint Surg Am 84-A(6):907–914
46. Yamamoto Y et al (2004) Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. Am J Sports Med 32(8):1825–1832
47. Yasuda K et al (2004) Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. Arthroscopy 20(10):1015–1025
48. Yasuda K et al (2006) Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: comparisons among 3 different procedures. Arthroscopy 22(3):240–251
49. Yasuda K et al (2008) An in vivo biomechanical study on the tension-versus-knee flexion angle curves of two grafts in anatomic double-bundle anterior cruciate ligament reconstruction: effects of initial tension and internal tibial rotation. Arthroscopy 24(3):276–284
50. Yasuda K et al (2010) Anatomic double-bundle anterior cruciate ligament reconstruction. Arthroscopy 26(9):S21–S34
51. Yasuda K et al (2012) A pilot study of anatomic double-bundle anterior cruciate ligament reconstruction with ligament remnant tissue preservation. Arthroscopy 28(3):343–353

Portals

23

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Stefano Zaffagnini, and Freddie H. Fu

23.1 Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the most frequent procedures in orthopedic sports medicine. Epidemiological studies estimate that more than 100,000 cases are done yearly in the USA [32, 33]. The single incision, or transtibial (TT), technique in which the femoral tunnel is drilled by passing the drill-bit through the tibial tunnel was widely used by orthopedic surgeons since the implementation of arthroscopic ACL reconstruction in the 1980s. Although very practical, the vertical non-anatomical orientation of the ACL graft achieved by this technique did not provide restoration of intact knee kinematics and joint stability [40, 52, 53, 58]. In the early 2000s, aiming for better long-term outcomes, the anatomy of the ACL was revisited. The ACL was shown to be non-isometric throughout the knee range of motion, and much emphasis was given to the presence of two synergistic, functional bundles: the anteromedial (AM) and posterolateral (PL) bundles [62]. The primary goals of ACL reconstruction were restoration of the native knee's complex biomechanics, particularly the knee's intrinsic rotational stability, and the prevention of early-onset degenerative changes [30, 35]. The perception that the ACL AM and PL bundles could be anatomically reconstructed by the use of the double-bundle ACL reconstruction emerged as a valuable option for surgeon to better restore knee anatomy and function [1, 57, 63]. Concurrently, many shifted from the TT to anatomic single-bundle (SB) ACL reconstruction, encouraged by its relative simplicity when compared to the steeper learning curve of the double-bundle (DB) technique. The continuously evolving anatomical reconstruction concepts have recently given rise to the individualized anatomic ACL concept. By respecting the multitude of anatomic variations, surgeons can match the graft characteristics, the surgical technique (SB or DB), and the tunnel diameter, position, orientation, and length to the individual bony and ligamentous anatomy of each patient to achieve the best possible outcomes [11, 17, 26, 31, 34, 61].

Using the best available evidence, this chapter reviews current concepts regarding the native ACL anatomy, the advantages of independently drilling the femoral tunnel, and technical notes given by three experts on how to achieve an anatomical femoral tunnel position with the use of three different accessory anteromedial portals.

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23.2 Native ACL Femoral Insertion Site

The native anatomy of the ACL has been exhaustively studied in an effort to achieve more anatomical reconstructions. The native femoral insertion site shape and size are of particular interest because, as opposed to the tibial insertion site, there is much controversy on where and how to properly position the femoral tunnel aperture for better anatomical positioning of the graft. In the mid-1970s, Dr. William Clancy Jr. described the “resident’s ridge,” a bony ridge on the lateral femoral condyle that delineates the anterior and superior edges of the ACL’s anatomic insertion on the femur [20, 21, 42]. The lateral femoral condyle notch’s bony anatomy was further dissected by Ferreti et al. who described the bifurcate ridge, a bony ridge that divides the ACL’s femoral insertion into its AM and PL attachments [9]. Studies have shown that as time elapses between injury and reconstruction, less ACL remnant remains to aid femoral guide pin placement [49, 60]. Thus, the bony landmarks of the femoral insertion site should be well understood by any surgeon attempting an ACL reconstruction; Piefer et al. performed a systematic review of the literature trying to better define the position and area of the ACL native femoral footprint [41]. The 20 studies included in the final sample were divided into three subgroups: radiographic, arthroscopic, and morphologic descriptions. The radiographic analysis results showed that the average center of the ACL is located 43 % from proximal to distal in a line parallel to the long axis of the femoral shaft and 2.5 mm anterior to the posterior part of the lateral femoral condyle. Kopf et al. performed another systematic review of anatomical studies done in cadaveric specimens, concluding that for the establishment of consistent reconstruction techniques, instead of relying on numeric descriptions or schematics extracted from the literature, it is better to combine an individualized analysis of both remnant and bony landmarks [24].

Additionally, the 10× magnification achieved by the modern arthroscope is an invaluable tool for defining the center of the native ACL footprint. Specifically, a 30° scope passed through the AM or central portal best visualizes the ACL femoral footprint with the least possible distortion [18, 19, 50]. Lateral portals may not give the surgeon a clear, frontal view of the femoral footprint. Their use is associated with additional disruption of the native anatomy by notchplasty and the use of 70° scopes that intrinsically distort images when compared with 30° scope on a low inclination view.

Finally, much emphasis in preserving the ACL remnant is given in the literature. Although only a minority of cases have viable ACL remnant fibers for ACL augmentation techniques, even a small contingent of preserved ACL remnant fibers can help to better evaluate each patient’s unique native insertion shape and size (Fig. 23.1). Further, the presence of mechanoreceptors and innervation in the remnants of the ACL could provide a relevant biological benefit to graft healing and proprioception [14, 28].

23.3 The Use of Anteromedial Portals for the Femoral Tunnel Creation

Choosing appropriate portals is a key step in the planning of every arthroscopic surgery. When attempting to execute an anatomic ACL reconstruction, it is imperative to attain optimal visualization of the native anatomy with unrestrained scope

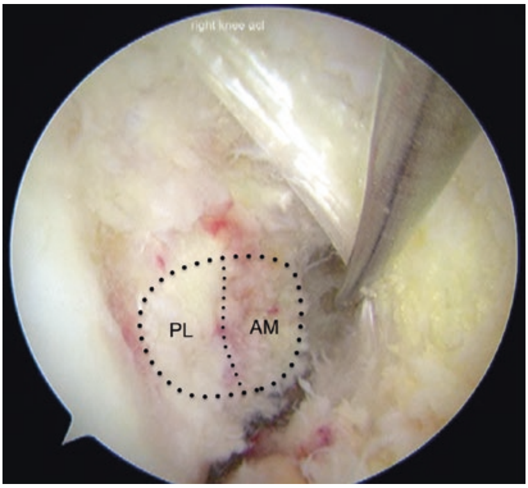

Fig. 23.1 ACL femoral remnant (*dotted lines*). *AM* ACL anteromedial bundle footprint, *PL* ACL posterolateral bundle footprint

movement. Below are the descriptions of three different techniques to reach anatomic positioning of the femoral tunnel using independent drilling through different accessory anteromedial portals.

23.4 Dr. Freddie Fu: High Anterolateral Portal, Central Anteromedial Portal, and Accessory Anteromedial Portal for Anatomic Double- or Single-Bundle ACL-R

The three-portal technique, which is described below, employs the high anterolateral portal (LP), the central anteromedial portal (CP), and the accessory anteromedial portal (AMP) (Fig. 23.2). It is best suited for anatomic SB or DB ACL reconstruction allowing an excellent balance between adequate three-dimensional visualization of the knee structures and optimal angle of attack for the instruments used for placing anatomic femoral tunnels [4].

Fig. 23.2 Dr. Freddie Fu portals. Thigh placed in a holder. Ink shows the patellar border and the portals. *PL* high anterolateral portal, *CP* anteromedial central portal, *AMP* accessory anteromedial portal

23.4.1 Technical Note (Description)

The arthroscopic step of ACL reconstruction begins with the LP incision using a #11 scalpel localized 1 cm lateral to the patellar ligament at the height of the distal border of the patella with the knee flexed to 90°. The incision is made by pointing the cutting surface proximally to avoid iatrogenic damage to the cartilage or the anterior horn of the lateral meniscus. Through this high anterolateral point of view, it is possible to have a clear view of the ACL tibial insertion site, as well as the medial, lateral, and patellofemoral compartments, without piercing the Hoffa fat pad.

With the knee flexed to 90°, the CP incision is then made with the assistance of a spinal needle inserted into the articular capsule, immediately above the joint line, through the medial third of the patellar tendon, under arthroscopic visualization through the LP. The correct position of the needle is in the distal third of the joint space, centralized to the intercondylar notch in the frontal plane. If the position is correct, it should be possible to orient the needle parallel to the ACL fibers (Fig. 23.3). When the proper position is reached, an incision with a #11 blade scalpel, with the cutting edge pointed proximally, is made carefully to avoid accidental damage to the intermeniscal ligament or the articular cartilage. The CP is of utmost importance, both for the direct visualization of the femoral origin of the ACL's bony and remnant landmarks and for the passage of the ACL tibial guide and associated instruments.

The last portal is once again made with the knee flexed to 90° and with the assistance of a spinal needle slowly advanced into the joint line. The position is approximately 2 cm medial to the medial border of the patellar ligament and should be placed slightly above the anterior horn of the medial meniscus. When pointing to the femoral origin of the ACL, the needle should be far enough from the medial femoral condyle to ensure no damage is done to the articular cartilage when drilling the tunnels (Fig. 23.4). The AMP is also used to place the tibial PL guide, set at 45°, when DB reconstruction is chosen. The

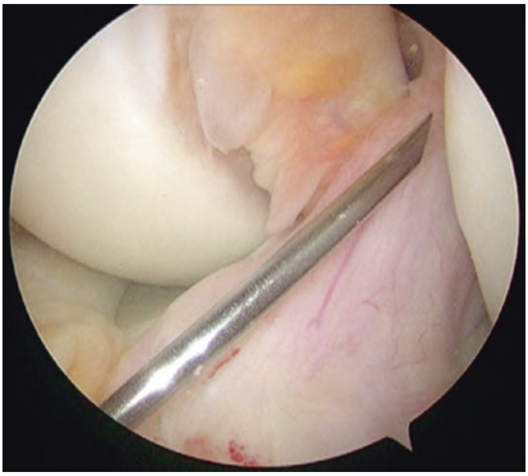

Fig. 23.3 Arthroscopic view of the creation of the CP viewed by the LP. The needle was advanced parallel to the ACL in the correct position for the creation of the CP

measurement of the femoral ACL footprint is made using the AMP as the visualization portal, while the LP portal is used for ruler insertion. The final visualization of the femoral tunnel position, integrity, and lateral cortex with the guide pins in position through the AMP can be achieved by the CP (Fig. 23.5).

23.5 Dr. William Clancy Jr.: Anterolateral Portal, Anteromedial Portal, and Superior Accessory Medial Portal in Figure 4 Position

An accessory medial portal gives the arthroscopist a better viewing angle of the resident's ridge, the bifurcate ridge, and the posterior wall of the lateral femoral condyle. However, both the lateral and medial portals can have limited viewing when one has to flex the knee past 90° vertical.

There is a third viewing option that overcomes the limitations as presented for lateral and medial viewing portals. This is a superior accessory anteromedial portal (SAM) first described by Dinesh Patel in the 1980s. The knee is placed in a figure four position, placing the operative leg over the contralateral leg. The borders of the medial aspect of the inferior patella and the superior medial femoral condyle are palpated. Just below, one can readily palpate a soft spot in the capsule. The scalpel blade is then gently directed inferolaterally, and the scope is introduced into the knee joint. This superior placement allows for a second lower medial portal that can be made in a horizontal fashion, for drilling of the ACL femoral tunnel (Fig. 23.6).

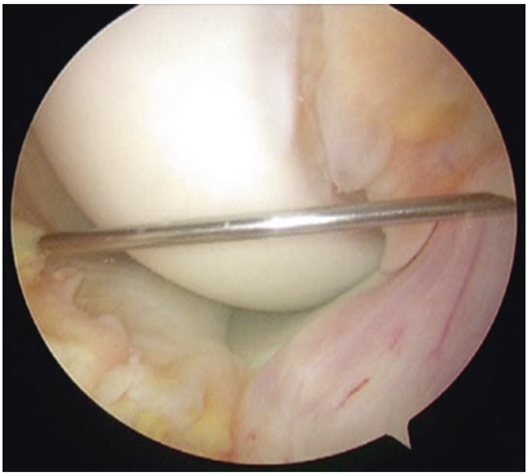

Fig. 23.4 Arthroscopic view of the creation of the AMP viewed by the LP. The needle is positioned just above the anterior horn of the medial meniscus and distant enough from the medial femoral condyle to allow femoral tunnel drilling without damaging the articular cartilage

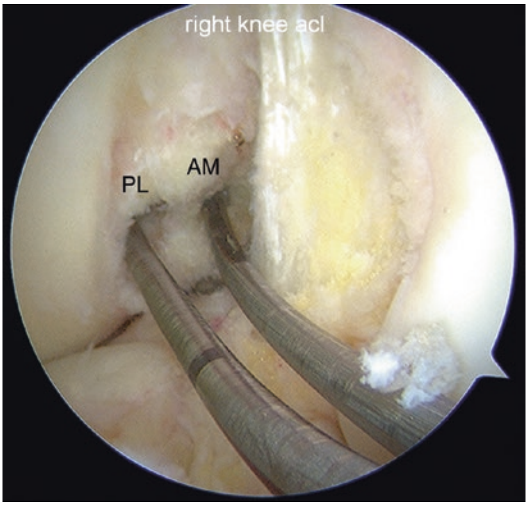

Fig. 23.5 Arthroscopic view of the DB femoral tunnels with flexible guide pins in place viewed by the CP. *AM* anteromedial tunnel, *PL* posterolateral tunnel

This portal essentially gives one an axial view of the entire lateral femoral condyle, particularly the relationship of the bifurcate ridge, the resident's ridge, and the posterior wall of the lateral

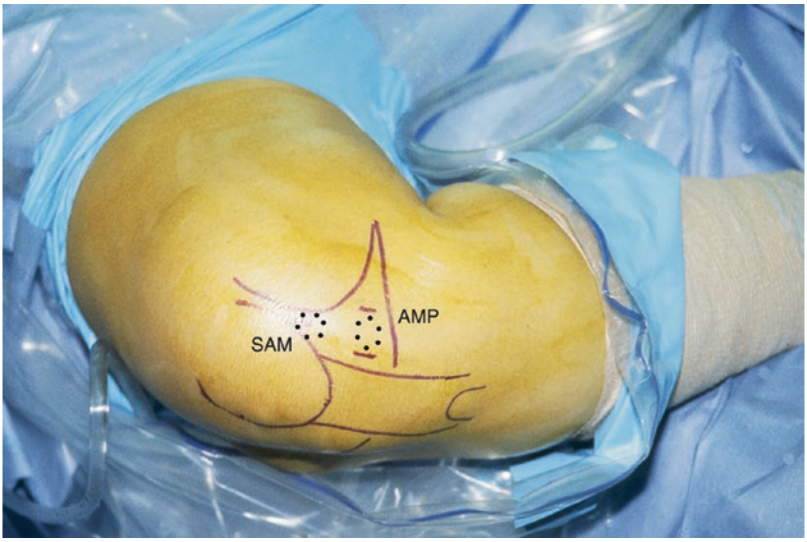

Fig. 23.6 Dr. William Clancy Jr. portals. The leg is placed in a figure 4 position. SAM. The superior accessory anteromedial portal is located just inferior to the inferior medial edge of the patella and the superior edge of the medial femoral condyle. *AMP* anteromedial portal

femoral condyle (Fig. 23.7a–c). This allows for greater accuracy of k-wire placement than any of the two other portals. Further with a little varus pressure, one can flex the knee more than 90° without compromising the view during k-wire placement and drilling of the tunnel.

When the knee is placed in 70–90° of knee flexion in a vertical position, the SAM provides an axial view of the tibial plateau where the relationship between the base of the tibial spine and the anterior aspect of the tibia and the menisci can be far more accurately assessed.

If one desires to be as objective as possible, I believe that the SAM provides better opportunity to achieve this.

23.6 Dr. Konsei Shino: Anterolateral Portal, Anteromedial Portal, and Far Anteromedial Portal for Inside-Out Rectangular Femoral Socket

This inside-out technique is not applicable to the knee without passive flexion over 140°, as less flexion results in blowout of the tunnel. In this deep flexion, reduced joint cavity volume may disturb view to the attachment area. Care must be taken to avoid damage to the articular cartilage of the medial femoral condyle.

Good fixation may be achieved with an interference screw, but not with a button around the tunnel opening on the lateral cortex because of softer bone quality and shorter tunnels in the physis. Thus, it is our opinion that this technique is applied for the anatomical rectangular tunnel ACL reconstruction with a bone-patellar tendon--bone graft or bone-quadriceps tendon graft, not for a round tunnel reconstruction with soft tissue graft [47, 48].

The distal thigh is kept horizontal using a leg holder with the calf hanging. In addition to the routine anterolateral (AL) and anteromedial (AM) portals, the far anteromedial (FAM) portal is created 2–2.5 cm posterior to the AM portal and just above the medial meniscus (Fig. 23.8) [46]. This portal makes it possible for instruments to get more perpendicular access to the ACL femoral attachment area on the lateral wall of the notch.

The fibrous tissue, including the ACL stump, on the superior-posterior half of the lateral wall of the intercondylar notch is thoroughly removed using a radiofrequency device through the FAM portal, while the posterior third of the lateral wall of the notch is simultaneously viewed via the AM portal with a 45° oblique arthroscope. Mechanical

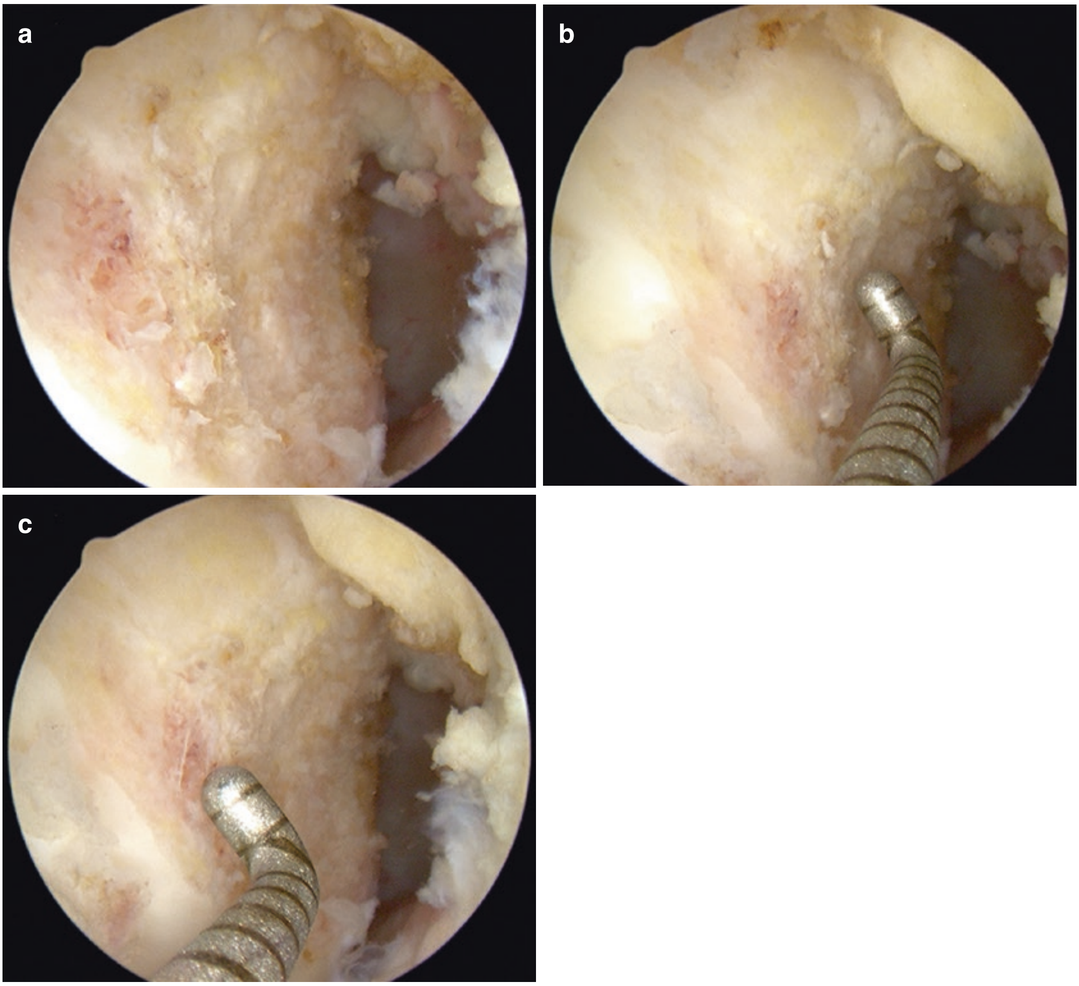

Fig. 23.7 Arthroscopic view of the lateral notch by the SAM. The SAM provides a more axial view of the landmarks of the lateral notch. (**a**) The lateral notch and its posterior edge. (**b**) The probe depicts the bifurcate ridge. (**c**) The probe denotes the insertion of the PL fibers of the ACL

shavers may not be utilized in order to preserve subtle undulation of the bony surface around the attachment area. After cleaning up, the attachment area is clearly delineated by the resident's ridge, anteriorly; upper cartilage margin, superiorly; and posterior cartilage margin, posteriorly (Fig. 23.9) [23, 42, 49].

Two points are marked with a 5-mm distance in the center of the attachment area along its long axis to the resident's ridge using radiofrequency device and a microfracture awl.

With the knee deeply flexed over 140° while viewing with the arthroscope via AM portal, two guide pins are drilled from the marked points to the lateral femoral cortex via the FAM portal and then overdrilled with a 5.0-mm cannulated acorn drill bit (Fig. 23.10). The two round holes are dilated into one parallelepiped socket with the 5 × 10-mm cannulated dilator (Figs. 23.11a, b and 23.12).

23.7 Accessory Anteromedial Portal in the Literature

Many authors experimentally studied the use of the AMP for the execution of the femoral socket in ACL reconstruction. Cadaveric specimens,

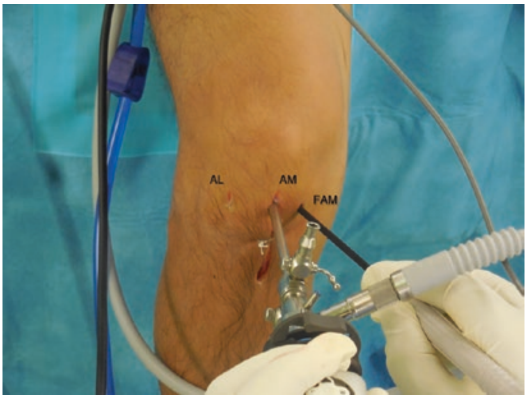

Fig. 23.8 Dr. Konsei Shino portals. Three arthroscopic portals: anterolateral (*AL*), anteromedial (*AM*), and far anteromedial (*FAM*) which is 2–2.5 cm posterior to the AM portal and just above the medial meniscus. The FAM portal makes it possible for instruments to get more perpendicular access to the ACL femoral attachment area

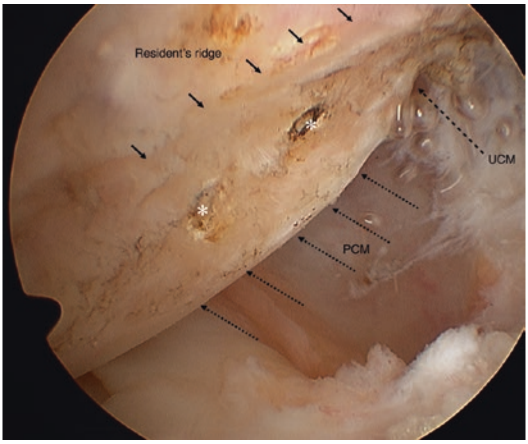

Fig. 23.9 Exposed ACL femoral attachment viewed through the AM portal, delineated by the "resident's ridge," by upper cartilage margin (*UCM*) and posterior cartilage margin (*PCM*). Two points (*) are marked with 5-mm distance in the center of the attachment area along its long axis or the resident's ridge using RF device and a microfracture awl

synthetic knee models, and computational knee models were evaluated with regard to the optimal knee flexion angle to achieve anatomic positioning of the guide pin for preparing the femoral socket [3, 5, 8, 15, 16, 36, 37, 39, 44, 55, 64]. Zantop et al. used 60 bone models to recreate the drilling of the PL bundle tunnel using three different simulated knee flexion angles at 70°, 90°, and 110°, in combination with either a low or a high AMP, to define which was the safest choice to avoid lateral femoral condyle cartilage damage [64]. The findings suggest that flexing the knee 110° and using the low AMP minimize the risk of cartilage damage. Nakamura et al. tested the same knee flexion angles in ten cadaveric specimens in combination with a FAM portal, also finding that higher knee flexion angles better avoid cartilage damage [37]. Farrow et al. utilized seven fresh frozen cadaveric knees to drill guide pins in the anatomical AM and PL bundle positions using an accessory anteromedial approach with 90°, 110°, and 130° of knee flexion [8]. The exit of the guide pins in the lateral femoral cortical bone was identified, and the distance between each pin and lateral gastrocnemius, articular cartilage of the lateral femoral condyle, and lateral collateral ligament were measured. Again, safer distances were achieved when the knee was flexed more than 110°. To better understand the influence of the knee flexion angle and the resulting tunnel length and inclination, Badeski et al. used nine cadaveric specimens with the knee flexed at 90°, 110°, and 130° to find increasingly horizontal PL bundle femoral tunnels and decreasing risk of femoral tunnel blowout when increasing knee flexion angles [5]. There is no clear consensus, but the majority of studies conclude that within a range of 100–130°, the resulting tunnels will have sufficient length to allow graft bone interface for proper fixation and graft healing. Lower flexion angles increase the odds of the guide pin hitting lateral structures like the common peroneal nerve, iliotibial tract, biceps tendon, popliteal tendon, lateral collateral ligament, and the lateral gastrocnemius. The risk of tunnel blowout and subchondral damage to the posterior aspect of the lateral femoral condyle was also associated with lower flexion angles. The optimal knee flexion angles vary with the shape and size of the ACL footprint that is being reconstructed. Higher flexion angles result in longer tunnels in comparison to decreased flexion angles. Controlling all of these variables to provide the best individualized treatment for every patient is challenging and requires meticulous planning and accomplishment.

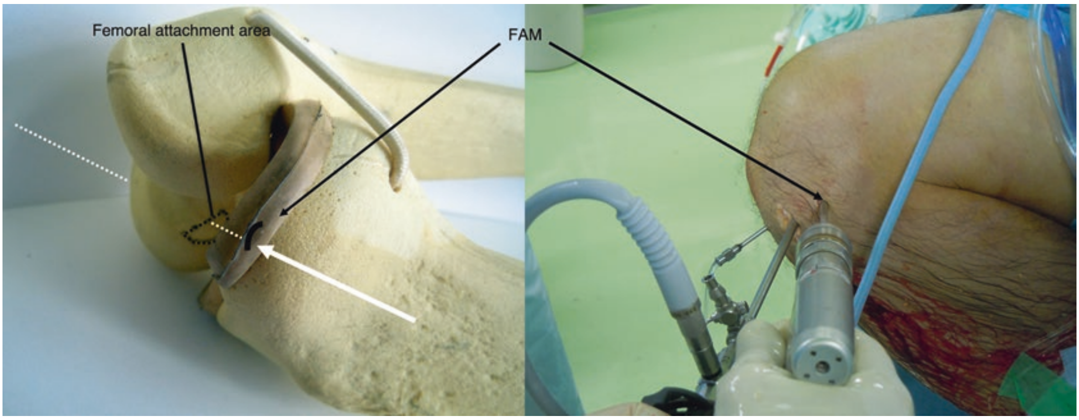

Fig. 23.10 Inside-out femoral tunnel drilling through the FAM portal in deep flexion of the right knee. With the knee flexed over 140°, drilling from the femoral attachment area to the lateral femoral cortex via the FAM portal is performed. *Left*. Instruments including drill bit are introduced through the FAM portal to the femoral attachment area. *Right*. Arthroscope is introduced through the AM portal

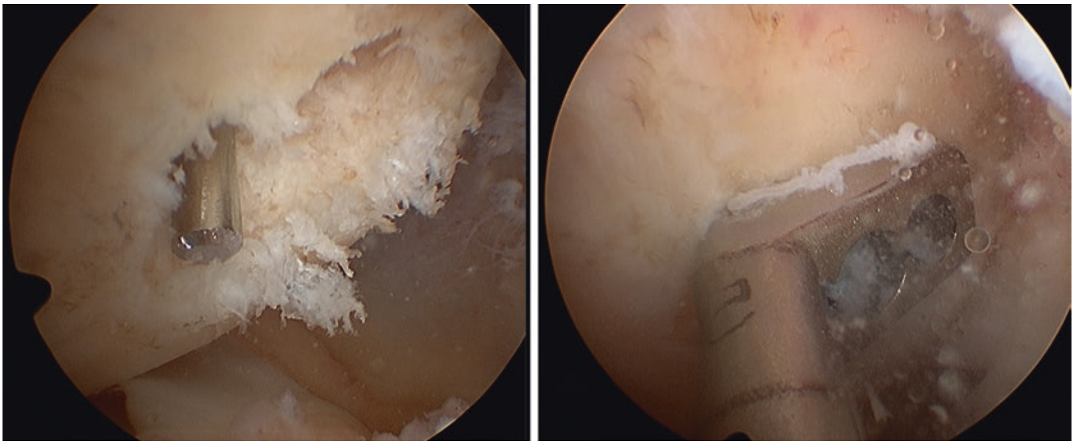

Fig. 23.11 Creation of the rectangular tunnel inside the femoral attachment area. *Left*. Two continuous round holes inside the attachment area. *Right*. The cannulated rectangular dilator in situ

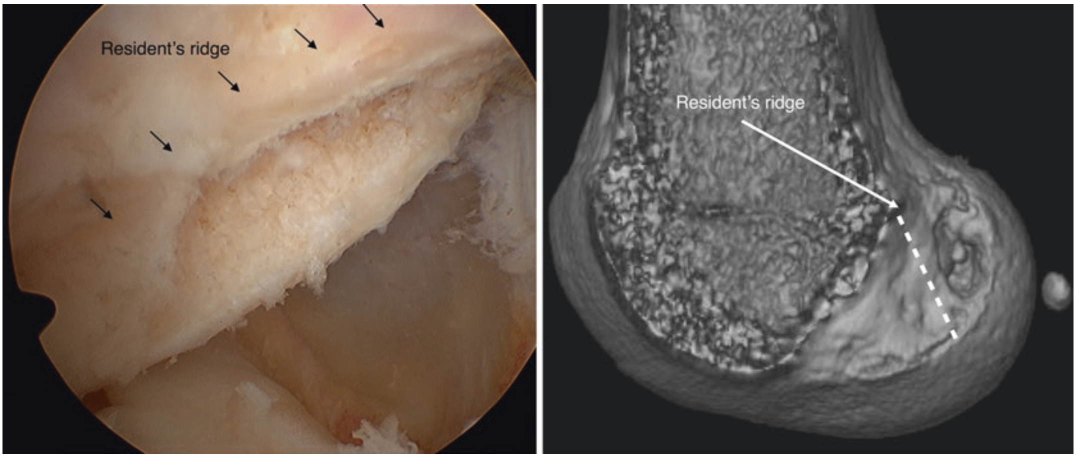

Fig. 23.12 Created rectangular tunnel aperture inside the femoral attachment area. *Left*. Arthroscopic view through the anteromedial portal. *Right*. 3D CT view

Comparison of the AMP techniques with the TT technique was also studied experimentally. Bedi et al. used 18 cadavers to compare the femoral tunnel length and obliquity at 100°, 110° and 120° of knee flexion, concluding that the higher the flexion angle, the more oblique the tunnels. This could lead to shorter tunnels and posterior cortical wall blowout [6]. The same author showed that at time zero, the AMP technique better restored the Lachman and pivot-shift test, while TT approach leads to enlargement of the tibial tunnel aperture due to the eccentric position and over-reaming in the posterolateral direction when trying to recreate the anatomic position [7]. Tudisco et al., on the other hand, found no significant difference on anteroposterior (AP) translation at time zero, but again found lower pivot shift with the AMP group than the TT group [2]. Many other studies found experimentally that the femoral tunnels were drilled closer to the anatomic position with adequate coverage of the footprint area by the use of the AMP technique as compared to the TT technique [12, 13, 54, 56].

Koutras et al. and Franceschi et al. showed that although the AMP techniques lead to more anatomical femoral sockets than the TT technique, no significantly better clinical outcomes were found [10, 27]. Noh et al. in a randomized controlled trial found that the Lysholm score and the AP translation were significantly improved in the AMP group in comparison to the TT group, while International Knee Documentation Committee (IKDC) and Tegner activity scale had no significant difference [38]. The Danish ACL Reconstruction Registry, a large prospective cohort, identified a higher rate of ACL re-tear with the use of the AMP technique explaining that higher in situ forces are experienced by the anatomically placed graft in comparison to a more vertical graft and that surgeons likely encounter a steep learning curve when shifting to an anatomical technique after years of using a TT technique [43]. To better understand the learning curve associated with transition from TT to AMP technique, Inderhaug et al. demonstrated significant improvement with regard to anatomical positioning of the femoral tunnel in a surgeon transitioning from TT to anatomical technique by providing post-op feedback by 3D CT scan after a first series of surgeries [22]. The assessment of the tunnel position by 3D CT scan regularly demonstrated that AMP and outside-in had similar results, both superior to TT groups [45, 51] (Takeda and Shin).

Although not always feasible, it is possible to achieve an anatomic femoral tunnel aperture position by the use of TT technique. Kopf et al. used the tibial tunnels created for a DB ACL reconstruction and the AMP in 113 patients to check if they could get guide pins to the center of the native femoral footprint and found that by the use of the AM tibial tunnel only, 4 % of the center of femoral footprints could be reached by the guide pin, followed by 64 % when using the PL tibial tunnel and 100 % using the AMP [25].

Biomechanically, Wang et al. demonstrated that SB ACL-R using an AMP better restored AP translation and rotational stability of the knee while limiting full extension in late stance phase of the gait when compared to TT technique [59].

Liu et al. performed a systematic review comparing TT and AMP techniques for the femoral socket creation, including three randomized control trials and six retrospective comparative studies, to further analyze both techniques' outcomes [29]. They found significantly better results in the AMP group on the basis of Lysholm, IKDC, and Visual Analogue Scale scores, although the differences were small and perhaps not clinically significant.

Conclusion

Anatomic positioning of the femoral tunnel is a crucial step in providing the best clinical outcomes following ACL reconstruction. This position makes it possible to choose between the different grafts, the different techniques (single bundle, double bundle, single-bundle augmentation, remnant preservation), the use of rectangular femoral socket for BPTB grafts, and different fixation devices. Good frontal visualization of the femoral footprint is invaluable for anatomic tunnel positioning. This multitude of possible technical combinations makes an AMP drilling technique the most versatile available technique for individualizing the treatment for every single patient.

Current systematic reviews show that the use of an AMP has better objective and patient-reported outcomes. However, the clinical relevance of this difference has yet to be proven. In the future, prospective, long-term studies are warranted to clarify which anatomical ACL reconstruction technique can give our patients the desirable outcome of joint stability, functional recovery, and prevention of early-onset degenerative joint changes.

References

1. Adachi N, Ochi M, Uchio Y, Iwasa J, Kuriwaka M, Ito Y (2004) Reconstruction of the anterior cruciate ligament. Single- versus double-bundle multistranded hamstring tendons. J Bone Joint Surg Br 86(4):515–520
2. Ahlden M, Samuelsson K, Fu FH, Musahl V, Karlsson J (2013) Rotatory knee laxity. Clin Sports Med 32)(1):37. doi:10.1016/j.csm.2012.08.005
3. Alavekios D, Peterson A, Patton J, McGarry MH, Lee TQ (2014) The relation between knee flexion angle and anterior cruciate ligament femoral tunnel characteristics: a cadaveric study comparing a standard and a far anteromedial portal. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 30(11):1468–1474. doi:10.1016/j.arthro.2014.05.031
4. Araujo PH, van Eck CF, Macalena JA, Fu FH (2011) Advances in the three-portal technique for anatomical single- or double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 19(8):1239–1242. doi:10.1007/s00167-011-1426-z
5. Basdekis G, Abisafi C, Christel P (2009) Effect of knee flexion angle on length and orientation of posterolateral femoral tunnel drilled through anteromedial portal during anatomic double-bundle anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 25(10):1108–1114. doi:10.1016/j.arthro.2009.05.018
6. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ 3rd (2010) Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 26(3):342–350. doi:10.1016/j.arthro.2009.12.006
7. Celentano U, Cardoso MPA, Martins CAQ, Ramirez CP, van Eck CF, Smolinski P, Fu FH (2012) Use of transtibial aimer via the accessory anteromedial portal to identify the center of the ACL footprint. Knee Surg Sports Traumatol Arthrosc 20(1):69–74. doi:10.1007/s00167-011-1574-1
8. Farrow LD, Parker RD (2010) The relationship of lateral anatomic structures to exiting guide pins during femoral tunnel preparation utilizing an accessory medial portal. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 18(6):747–753. doi:10.1007/s00167-009-0902-1
9. Ferretti M, Ekdahl M, Shen W, Fu FH (2007) Osseous landmarks of the femoral attachment of the anterior cruciate ligament: an anatomic study. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 23(11):1218–1225. doi:10.1016/j.arthro.2007.09.008
10. Franceschi F, Papalia R, Rizzello G, Del Buono A, Maffulli N, Denaro V (2013) Anteromedial portal versus transtibial drilling techniques in anterior cruciate ligament reconstruction: any clinical relevance? A retrospective comparative study. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(8):1330–1337. doi:10.1016/j.arthro.2013.05.020
11. Fu FH, van Eck CF, Tashman S, Irrgang JJ, Moreland MS (2015) Anatomic anterior cruciate ligament reconstruction: a changing paradigm. Knee Surg Sports Traumatol Arthrosc 23(3):640–648. doi:10.1007/s00167-014-3209-9
12. Gadikota HR, Sim JA, Hosseini A, Gill TJ, Li G (2012) The relationship between femoral tunnels created by the transtibial, anteromedial portal, and outside-in techniques and the anterior cruciate ligament footprint. Am J Sports Med 40(4):882–888. doi:10.1177/0363546511434276
13. Gavriilidis I, Motsis EK, Pakos EE, Georgoulis AD, Mitsionis G, Xenakis TA (2008) Transtibial versus anteromedial portal of the femoral tunnel in ACL reconstruction: a cadaveric study. Knee 15(5):364–367. doi:10.1016/j.knee.2008.05.004
14. Georgoulis AD, Pappa L, Moebius U, Malamou-Mitsi V, Pappa S, Papageorgiou CO, Agnantis NJ, Soucacos PN (2001) The presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL autograft. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 9(6):364–368. doi:10.1007/s001670100240
15. Hall MP, Ryzewicz M, Walsh PJ, Sherman OH (2009) Risk of iatrogenic injury to the peroneal nerve during posterolateral femoral tunnel placement in double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 37(1):109–113. doi:10.1177/0363546508324177
16. Hensler D, Working ZM, Illingworth KD, Thorhauer ED, Tashman S, Fu FH (2011) Medial portal drilling: effects on the femoral tunnel aperture morphology during anterior cruciate ligament reconstruction. J Bone Joint Surg Am 93(22):2063–2071. doi:10.2106/jbjs.j.01705
17. Hofbauer M, Muller B, Murawski CD, van Eck CF, Fu FH (2014) The concept of individualized anatomic anterior cruciate ligament (ACL) reconstruction. Knee Surg Sports Traumatol Arthrosc 22(5):979–986. doi:10.1007/s00167-013-2562-4

18. Hoshino Y, Rothrauff BB, Hensler D, Fu FH, Musahl V (2014) Arthroscopic image distortion-part I: the effect of lens and viewing angles in a 2-dimensional in vitro model. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA. doi:10.1007/s00167-014-3336-3
19. Hoshino Y, Rothrauff BB, Hensler D, Fu FH, Musahl V (2014) Arthroscopic image distortion-part II: the effect of lens angle and portal location in a 3D knee model. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA. doi:10.1007/s00167-014-3268-y
20. Hutchinson MR, Ash SA (2003) Resident's ridge: assessing the cortical thickness of the lateral wall and roof of the intercondylar notch. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 19(9):931–935
21. Hutchinson MR, Bae TS (2001) Reproducibility of anatomic tibial landmarks for anterior cruciate ligament reconstructions. Am J Sports Med 29(6):777–780
22. Inderhaug E, Larsen A, Strand T, Waaler PA, Solheim E (2014) The effect of feedback from post-operative 3D CT on placement of femoral tunnels in single--bundle anatomic ACL reconstruction. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA. doi:10.1007/s00167-014-3355-0
23. Iwahashi T, Shino K, Nakata K, Otsubo H, Suzuki T, Amano H, Nakamura N (2010) Direct anterior cruciate ligament insertion to the femur assessed by histology and 3-dimensional volume-rendered computed tomography. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 26(9 Suppl):S13–S20. doi:10.1016/j.arthro.2010.01.023
24. Kopf S, Musahl V, Tashman S, Szczodry M, Shen W, Fu FH (2009) A systematic review of the femoral origin and tibial insertion morphology of the ACL. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 17(3):213–219. doi:10.1007/s00167-008-0709-5
25. Kopf S, Pombo MW, Shen W, Irrgang JJ, Fu FH (2011) The ability of 3 different approaches to restore the anatomic anteromedial bundle femoral insertion site during anatomic anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 27(2):200–206. doi:10.1016/j.arthro.2010.07.010
26. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH (2011) Size variability of the human anterior cruciate ligament insertion sites. Am J Sports Med 39(1):108–113. doi:10.1177/0363546510377399
27. Koutras G, Papadopoulos P, Terzidis IP, Gigis I, Pappas E (2013) Short-term functional and clinical outcomes after ACL reconstruction with hamstrings autograft: transtibial versus anteromedial portal technique. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 21(8):1904–1909. doi:10.1007/s00167-012-2323-9
28. Lee BI, Min KD, Choi HS, Kwon SW, Chun DI, Yun ES, Lee DW, Jin SY, Yoo JH (2009) Immunohistochemical study of mechanoreceptors in the tibial remnant of the ruptured anterior cruciate ligament in human knees. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 17(9):1095–1101. doi:10.1007/s00167-009-0831-z
29. Liu A, Sun M, Ma C, Chen Y, Xue X, Guo P, Shi Z, Yan S (2015) Clinical outcomes of transtibial versus anteromedial drilling techniques to prepare the femoral tunnel during anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA. doi:10.1007/s00167-015-3672-y
30. Lohmander LS, Englund PM, Dahl LL, Roos EM (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769. doi:10.1177/0363546507307396
31. Lu W, Zhu W, Peng L, Fen W, Li H, Ou Y, Liu H, Wang D, Zeng Y (2015) Femoral footprint variation of the posterolateral bundle of the anterior cruciate ligament and double-bundle reconstruction. Knee 22(3):169–173. doi:10.1016/j.knee.2014.10.009
32. Lyman S, Koulouvaris P, Sherman S, Do H, Mandl LA, Marx RG (2009) Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. J Bone Joint Surg Am 91(10):2321–2328. doi:10.2106/jbjs.h.00539
33. Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR Jr, Paletta GA Jr (2014) Incidence and trends of anterior cruciate ligament reconstruction in the United States. Am J Sports Med 42(10):2363–2370. doi:10.1177/0363546514542796
34. Middleton KK, Hamilton T, Irrgang JJ, Karlsson J, Harner CD, Fu FH (2014) Anatomic anterior cruciate ligament (ACL) reconstruction: a global perspective. Part 1. Knee Surg Sports Traumatol Arthrosc 22(7):1467–1482. doi:10.1007/s00167-014-2846-3
35. Murawski CD, Wolf MR, Araki D, Muller B, Tashman S, Fu FH (2013) Anatomic anterior cruciate ligament reconstruction: current concepts and future perspective. Cartilage4(3):27S–37S.doi:10.1177/1947603513486557
36. Nakamae A, Ochi M, Adachi N, Deie M, Nakasa T, Kamei G, Okuhara A, Niimoto T, Ohkawa S (2014) Far anteromedial portal technique for posterolateral femoral tunnel drilling in anatomic double-bundle anterior cruciate ligament reconstruction: a cadaveric study. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 22(1):181–187. doi:10.1007/s00167-012-2346-2
37. Nakamura M, Deie M, Shibuya H, Nakamae A, Adachi N, Aoyama H, Ochi M (2009) Potential risks of femoral tunnel drilling through the far anteromedial portal: a cadaveric study. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 25(5):481–487. doi:10.1016/j.arthro.2008.11.010
38. Noh JH, Roh YH, Yang BG, Yi SR, Lee SY (2013) Femoral tunnel position on conventional magnetic resonance imaging after anterior cruciate ligament reconstruction in young men: transtibial technique versus anteromedial portal technique. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(5):882–890. doi:10.1016/j.arthro.2013.01.025

39. Osaki K, Okazaki K, Tashiro Y, Matsubara H, Iwamoto Y (2015) Influences of knee flexion angle and portal position on the location of femoral tunnel outlet in anterior cruciate ligament reconstruction with anteromedial portal technique. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 23(3):777–784. doi:10.1007/s00167-013-2705-7
40. Papannagari R, Gill TJ, Defrate LE, Moses JM, Petruska AJ, Li G (2006) In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation. Am J Sports Med 34(12):2006–2012. doi:10.1177/0363546506290403
41. Piefer JW, Pflugner TR, Hwang MD, Lubowitz JH (2012) Anterior cruciate ligament femoral footprint anatomy: systematic review of the 21st century literature. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 28(6):872–881. doi:10.1016/j.arthro.2011.11.026
42. Purnell ML, Larson AI, Clancy W (2008) Anterior cruciate ligament insertions on the tibia and femur and their relationships to critical bony landmarks using high-resolution volume-rendering computed tomography. Am J Sports Med 36(11):2083–2090. doi:10.1177/0363546508319896
43. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC (2013) Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(1):98–105. doi:10.1016/j.arthro.2012.09.009
44. Robert HE, Bouguennec N, Vogeli D, Berton E, Bowen M (2013) Coverage of the anterior cruciate ligament femoral footprint using 3 different approaches in single-bundle reconstruction: a cadaveric study analyzed by 3-dimensional computed tomography. Am J Sports Med 41(10):2375–2383. doi:10.1177/0363546513498989
45. Shin YS, Ro KH, Lee JH, Lee DH (2013) Location of the femoral tunnel aperture in single-bundle anterior cruciate ligament reconstruction: comparison of the transtibial, anteromedial portal, and outside-in techniques. Am J Sports Med 41(11):2533–2539. doi:10.1177/0363546513500764
46. Shino K, Horibe S, Hamada M, Nakamura N, Nakata K, Mae T, Toritsuka Y (2002) Allograft anterior cruciate ligament reconstruction. Tech Knee Surg 1:78–85
47. Shino K, Nakata K, Nakamura N, Toritsuka Y, Horibe S, Nakagawa S, Suzuki T (2008) Rectangular tunnel double-bundle anterior cruciate ligament reconstruction with bone-patellar tendon-bone graft to mimic natural fiber arrangement. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 24(10):1178–1183. doi:10.1016/j.arthro.2008.06.010
48. Shino K, Nakata K, Nakamura N, Toritsuka Y, Nakagawa S, Horibe S (2005) Anatomically oriented anterior cruciate ligament reconstruction with a bone--patellar tendon-bone graft via rectangular socket and tunnel: a snug-fit and impingement-free grafting technique. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 21(11):1402. doi:10.1016/j.arthro.2005.08.017
49. Shino K, Suzuki T, Iwahashi T, Mae T, Nakamura N, Nakata K, Nakagawa S (2010) The resident's ridge as an arthroscopic landmark for anatomical femoral tunnel drilling in ACL reconstruction. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 18(9):1164–1168. doi:10.1007/s00167-009-0979-6
50. Sutter EG, Anderson JA, Garrett WE Jr (2015) Direct visualization of existing footprint and outside-in drilling of the femoral tunnel in anterior cruciate ligament reconstruction in the knee. Arthrosc Tech 4(2):e107–e113. doi:10.1016/j.eats.2014.11.017
51. Takeda Y, Iwame T, Takasago T, Kondo K, Goto T, Fujii K, Naruse A (2013) Comparison of tunnel orientation between transtibial and anteromedial portal techniques for anatomic double-bundle anterior cruciate ligament reconstruction using 3-dimensional computed tomography. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(2):195–204. doi:10.1016/j.arthro.2012.08.020
52. Tashman S, Kolowich P, Collon D, Anderson K, Anderst W (2007) Dynamic function of the ACL--reconstructed knee during running. Clin Orthop Relat Res 454:66–73. doi:10.1097/BLO.0b013e31802bab3e
53. Thompson S, Salmon L, Waller A, Linklater J, Roe J, Pinczewski L (2015) Twenty-year outcomes of a longitudinal prospective evaluation of isolated endoscopic anterior cruciate ligament reconstruction with patellar tendon autografts. Am J Sports Med. doi:10.1177/0363546515591263
54. Tompkins M, Cosgrove CT, Milewski MD, Brockmeier SF, Hart JM, Miller MD (2013) Anterior cruciate ligament reconstruction femoral tunnel characteristics using an accessory medial portal versus traditional transtibial drilling. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(3):550–555. doi:10.1016/j.arthro.2012.10.030
55. Tompkins M, Milewski MD, Carson EW, Brockmeier SF, Hamann JC, Hart JM, Miller MD (2013) Femoral tunnel length in primary anterior cruciate ligament reconstruction using an accessory medial portal. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 29(2):238–243. doi:10.1016/j.arthro.2012.08.019
56. Tudisco C, Bisicchia S (2012) Drilling the femoral tunnel during ACL reconstruction: transtibial versus anteromedial portal techniques. Orthopedics 35(8):e1166–e1172. doi:10.3928/01477447-20120725-14
57. van Eck CF, Lesniak BP, Schreiber VM, Fu FH (2010) Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthrosc-J Arthrosc Relat Surg 26(2):258–268. doi:10.1016/j.arthro.2009.07.027

58. Wang H, Fleischli JE, Hutchinson ID, Zheng NN (2014) Knee moment and shear force are correlated with femoral tunnel orientation after single-bundle anterior cruciate ligament reconstruction. Am J Sports Med 42(10):2377–2385. doi:10.1177/0363546514541232
59. Wang H, Fleischli JE, Zheng NN (2013) Transtibial versus anteromedial portal technique in single-bundle anterior cruciate ligament reconstruction: outcomes of knee joint kinematics during walking. Am J Sports Med 41(8):1847–1856. doi:10.1177/0363546513490663
60. Wittstein J, Kaseta M, Sullivan R, Garrett WE (2009) Incidence of the remnant femoral attachment of the ruptured ACL. Clin Orthop Relat Res 467(10):2691–2694. doi:10.1007/s11999-009-0805-y
61. Wolf MR, Murawski CD, van Diek FM, van Eck CF, Huang YH, Fu FH (2015) Intercondylar notch dimensions and graft failure after single- and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 23(3):680–686. doi:10.1007/s00167-014-3414-6
62. Yoo YS, Jeong WS, Shetty NS, Ingham SJ, Smolinski P, Fu F (2010) Changes in ACL length at different knee flexion angles: an in vivo biomechanical study. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 18(3):292–297. doi:10.1007/s00167-009-0932-8
63. Zaffagnini S, Marcheggiani Muccioli GM, Lopomo N, Signorelli C, Bonanzinga T, Musiani C, Vassilis P, Nitri M, Marcacci M (2012) Can the pivot-shift be eliminated by anatomic double-bundle anterior cruciate ligament reconstruction? Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 20(4):743–751. doi:10.1007/s00167-012-1897-
64. Zantop T, Haase AK, Fu FH, Petersen W (2008) Potential risk of cartilage damage in double bundle ACL reconstruction: impact of knee flexion angle and portal location on the femoral PL bundle tunnel. Arch Orthop Trauma Surg 128(5):509–513. doi:10.1007/s00402-007-0480-y

Press-Fit ACL Reconstruction

24

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24.1 Introduction

Several factors, such as timing of surgery, graft choice, tunnel positioning, graft tensioning, graft fixation methods, and the postoperative rehabilitation protocols, play a very important role in a successful ACL reconstruction [1]. PBTB and hamstring are the most commonly used grafts with equally successful long-term results [2]. Quadriceps tendon is emerging as an attractive alternative because of its predictable thickness and less donor site morbidity [3].

Stable graft fixation is paramount for a successful outcome as the graft relies on its initial stability for the first 6–8 weeks. Various absorbable and nonabsorbable implants in the form of screws, stables, pins, and buttons have been used. Although, these implants provide good initial stability for accelerated rehabilitation, they can be associated with implant migration, osteolysis, and soft tissue irritation. They can also increase the complexity of revision surgery. Cost is another important issue and implants can produce signal interference during subsequent MRI imaging. To avoid all these issues with nonbiological implants, Peter Hertel [4] introduced a novel concept of press-fit PBTB graft fixation in 1987.

Initial description of this technique was for mini-open ACL reconstructions, but over the last two decades, its use has been extended to all arthroscopic, different graft types, and other ligament reconstructions. Biomechanical strength testing results have been promising and various authors have published good long-term clinical results [4–6]. This chapter will discuss the history, biomechanical evidence, surgical techniques, and results of press-fit ACL reconstruction.

24.2 History and Surgical Techniques

Peter Hertel originally developed this technique for femoral-sided press-fit fixation [4] of patellar BTB graft, but in 1989, he extended it to tibial-sided fixations as well. This technique uses the bone plugs on either end of patellar tendon graft for press-fit fixation in slightly undersized bony tunnels. He used medial third of the patellar

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tendon. Patellar bone plug was harvested in the form of shallow disk 5 mm in depth and tibial bone block in almost square cross section about 0.5 mm wider than the diameter of the femoral tunnel. A mini-arthrotomy was made through donor site defect. Femoral tunnel was drilled with 8 mm hollow reamer from inside out and dilated to 9 mm with tunnel dilator. A tibial bone plug of 9.5 mm is then tapped into femoral tunnel from inside out, until flush with joint surface. A tibial tunnel was drilled in a standard fashion with the same hollow reamer. A 5 mm bone block was cut out above the tibial drill hole. The tibial trough was deepened with a chisel. Then, the patellar bone block was driven into the gap of the chisel securing the graft [4].

In 1993, Boszotta et al. developed an arthroscopic technique using an oscillating hollow saw for rapid and standardized harvesting of cylindrical bone plugs, ensuring safe and adequate femoral press-fit fixation [7]. An analogous technique was used for quadriceps and later published in a variation by Barie et al. [8] and Akoto et al. [9]. Gobbi created a single femoral conical press-fit fixation as an outside in implantation in 1994 [10].

G. Felmet developed his own patellar BTB “all press-fit” technique in 1995 [11, 12]. He used self-adapted bottom to top (BTT) fixation and tensioning. This allowed a press-fit fixation near the original insertion on both tibial and femoral side. In 1998, he introduced different diameter hollow reamers to harvest different sized bone cylinders in a precise and reproducible manner [13] (Figs. 24.1, 24.2, and 24.4).

From 1997 onwards, G. Felmet used quadriceps tendon as a bone-tendon graft for revision surgery. He filled the tunnel defect on both sides with bone cylinder and fixed simultaneously the graft press fit in self-adapted BTT fixation [13]. A similar method was developed later by Huber J using a oscillating saw [8]. Simultaneously and independently, A. Halder developed his double press-fit fixation with patellar tendon BTB graft commonly fixed and tensioned top down [14].

In 1998, H. Pässler and Mastrokalos described the first material-free ACL reconstruction with hamstring autograft [15]. Semitendinosus and gracilis tendons both were tied together with a simple knot. A bottleneck-like tunnel is created on the femoral side, in which the knot of the tendon loop is firmly secured just proximal to the cortex of notch wall at the anatomical insertion, hence avoiding any bungee effect described with suspensory fixation. On the tibial side, the graft was fixed with sutures over a bone bridge. A variation with a supplemented bone cylinder instead of the knot has been reported by Liu et al. [16]. G. Felmet also developed his press-fit technique for hamstring graft, which will be discussed in detail later in this chapter [17, 18] (Figs. 24.2, 24.3, and 24.4).

Hybrid fixation has also been described with femoral press-fit and tibial fixation with implants [10, 19]. Prado et al. in 2004 created a femoral implant-free hamstring double-bundle reconstruction over a bone bridge inside out and outside in which was fixed with an interference screw on the tibial side [20].

Studies and results are listed in Table 24.1.

24.3 Stability of Fixation

Biomechanical strength testing of press-fit techniques has been performed by several investigators. Most of the work has been done on the femoral-sided fixation. Rupp et al. compared femoral press-fit fixation with biodegradable and titanium interference screw in porcine lower limbs. He found significantly higher ultimate loads in screw compared to press-fit fixation [21]. Musahl et al. also compared press-fit femoral fixation with interference screw fixation in hind limbs of Saanen breed goats. In his analysis, no statistically significant difference was found between two groups based the cyclic creep tests and uniaxial tensile loading. But he also noted lower ultimate load for press-fit fixation vs screw fixation. Data from their study supported early functional post-op rehab regimens but suggested tailoring rehab protocols to allow bone healing [22]. Seil et al. used a cyclic loading protocol in porcine lower limbs. The press-fit group failed in five specimens [23]. The authors concluded that press-fit fixation is not secure enough for accelerated rehabilitation protocol.

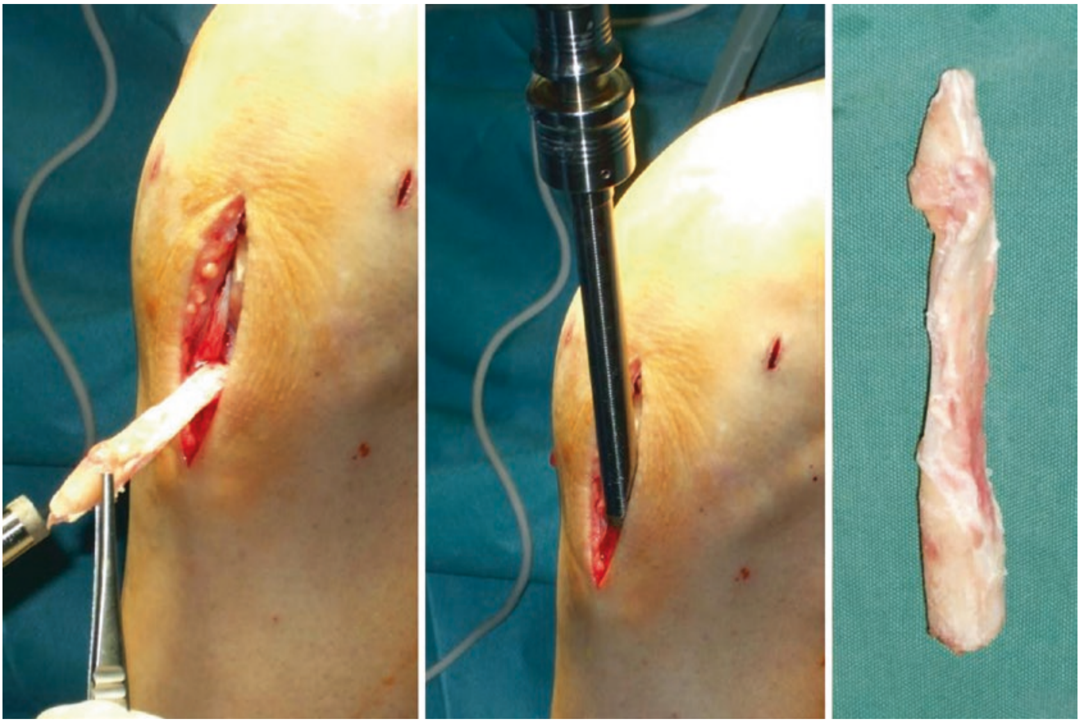


Fig. 24.1 A 9 mm hollow miller is inserted in a flat angle over the distal patellar. The so harvested half cylinder with the central third of the patellar tendon is given into the 11 mm miller, and a 2–3 cm bone cylinder is milled out. A patellar BTB graft is harvested with a 9 and 11 mm bone cylinder on each side

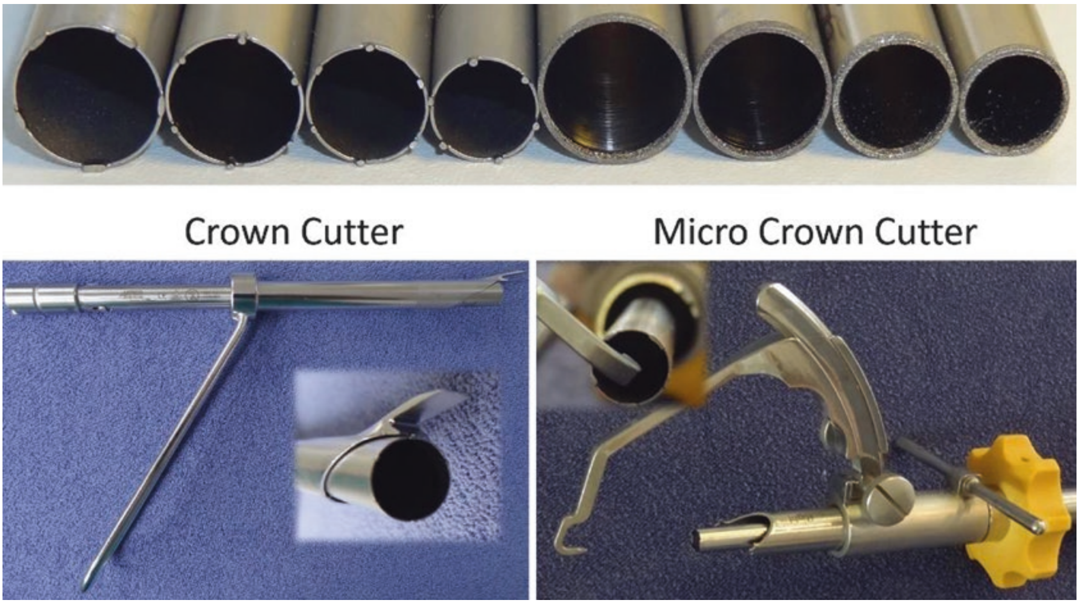


Fig. 24.2 Tubed guiding devices for femur (*left*) and tibia (*right*) allow guiding for diamond wet grinding and crown cutter hollow miller. Diameters range from 8 to 11 mm

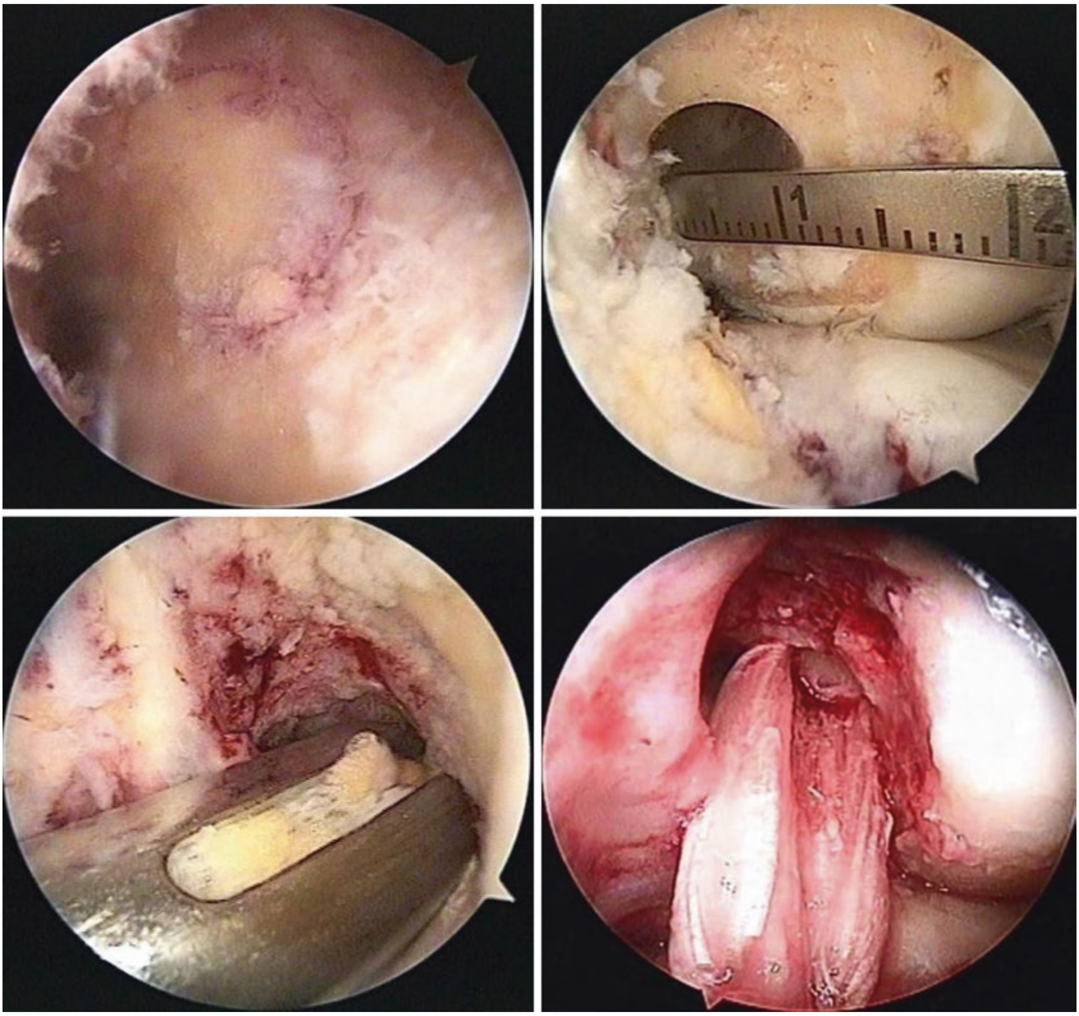
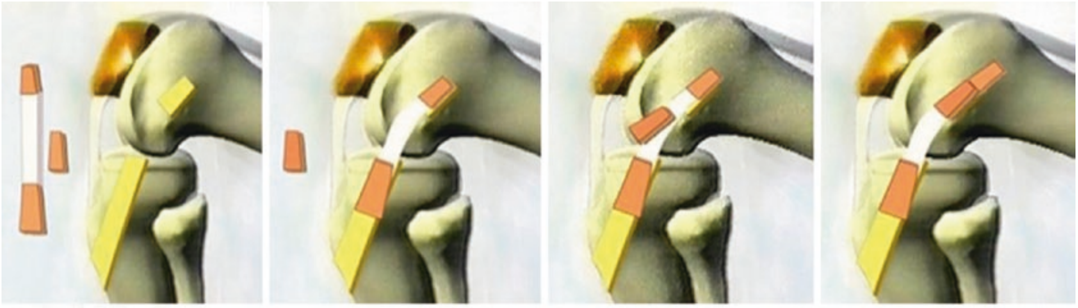


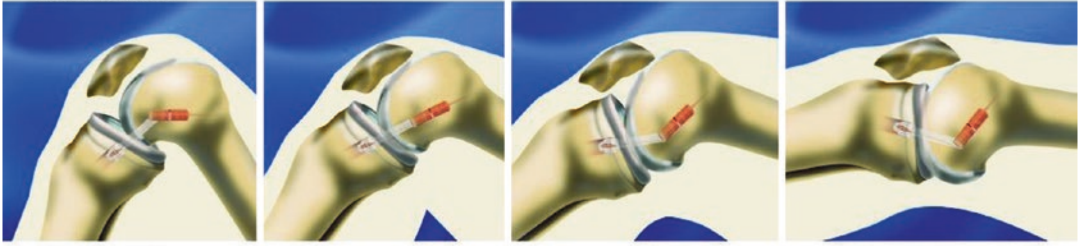
Fig. 24.3 The femoral tunnel is placed at the original insertion and proved after a probe cutting through the anteromedial portal. The tunnel has to overlap the intermediate ridge between AM and PL bundle insertion. The individual size from 8 to 11 mm can be measured by a ruler. The crescent-shaped femoral insertion mimics the two bundles

On the contrary, Lee et al. compared femoral press-fit fixation performed with a 1.4 mm oversized bone plug to interference screw and reported no difference in stiffness and linear load or failure mode [24]. Kuhne et al. reported average primary stability of 570 N (±100 N) for the bone-blocking BTB technique and 402 N (±79 N) for the interference screw fixation [25]. Mayr et al. reported the same fixation properties for press-fit dowel (slashed circle 7 mm) with 100 N axial load and interference screw [26].

Authors have also investigated effect of variables like loading direction, the length of bone plug, and method of preparation for femoral tunnel. Schmidt Wiethoff measured a failure rate of 333 N for 25 mm length and recommended a length of the bone cylinder by 20–30 mm [27]. Pavlik et al. measured a ultimate tensile strength of 534 N at 45° [28] and Seil et al. at an angle of 80° between load axis and tunnel axis with 708 N (± 211) [19]. Dargel et al. found a higher fixation quality for a dilated tunnel up to 1 mm, thereby compacting cancellous bone [29]. He also reported comparable failure loads for quadriceps tendon patellar bone and patellar BTB in a cadaveric study. Kilner et al. [30] compared knot/press-



Patella-BTB graft



Hamstring graft

Fig. 24.4 *Above*: the BTB graft is implanted from distal through the tibial tunnel. The distal bone cylinder is impacted press fit under the tibial plateau. The proximal bone cylinder is impacted in 120° knee flexion into the femoral tunnel. The bone cylinder harvested from the femoral tunnel is impacted and fixes the graft at the original insertion under tension. *Below*: the hamstring/quadriceps graft is implanted from distal through the tibial tunnel. The distal bone cylinder is impacted press fit under the tibial plateau (*left*). The proximal graft is tensioned in 120° knee flexion. The bone cylinder harvested from the femoral tunnel is impacted and fixes the graft at the original insertion. In extension the BTT (*bottom* to *top*) fixation is self-adapted tensioning the graft (*right*)

fit technique for hamstring with commonly used endobutton technique and found no difference in anterior tibial translation in response to anterior tibial load. Stiffness of the knot/press-fit complex was found to be 37.8 N/mm, and the load at failure was 540 N, which was comparable with other devices. Similar findings were noted for knot/press-fit hamstring by Lin et al. [16].

Press-fit tibial fixation has been compared with other commonly used methods. Boszotta et al. showed a significantly higher primary stability of 758 N (range, 513–993 N) for press-fit fixation in comparison to interference screw 572 N (range, 473–680 N), staple 608.4 N (range, 511–727 N), and suture over a bone bridge 304.5 N (range, 120–327 N) [31]. Jagodzinski et al. found the highest maximum load to failure for the extra tape fixed press-fit fixation at 970 ± 83 N, followed by the interference screw fixation with 544 ± 109 N, and the suture press-fit fixation with 402 ± 78 N [32]. In a porcine femur model, Ettinger et al. found that a tibial press-fit technique that uses an additional bone block has better maximum load to failure compared to an interference screw fixation. But for the bone block fixation only technique (author's technique), it was found to be 290 ± 74 N only [33]. The same group investigated the tibial PCL fixation. The maximum load to failure was 518 ± 157 N for the hamstring with a knot, 558 ± 119 N for the interference screw, and 620 ± 102 N (541–699 N) for the quadriceps tendon bone block [34].

24.4 Techniques for All Press Fit

24.4.1 Patellar Bone-Tendon-Bone (BTB)

The use of diamond wet grinding hollow milling cutter (Surgical Diamond Instruments, SDI) since 1998 gave us a reproducible precision of 0.2 mm of the bone dowels for the press-fit fixa-

Table 24.1 Techniques and outcomes of different grafts for press-fit and hybrid fixation (at the tibial side): Hertel et al. [5], Gobi et al. [10], Felmet [36], Al-Husseiny et al. [19], Pavlik et al. [37], Wipfler et al. [38], Halder [14], Felmet [39], Barie et al. [53], Widuchowski et al. [41], and Akoto et al. [9]

	Hertel	Gobbi et al.	Felmet	Al-Husseiny et al.	Pavlik et al.	Wipfler et al.	Wipfler et al.	Halder	Felmet	Barie et al.	Widuchoswski et al.	Akoto et al.
Year	1987–1991	1994–1995	1998–2000	1998–2000	1998–2002	1998–1999	1998–1999		2003–2005	2007–2008		2010
Graft	BTB	BTB	BTB	BTB	BTB	BTB	Hamstring	BTB	Hamstring	Quadriceps TB	BTB	Quadriceps TB
Technique Femur	Press fit	Conical press fit	Press fit BTT (bottom to top) self-adapted	Press fit	Press fit	Press fit	Knot in bottle neck	Press fit	Press fit BTT self-adapted	Press fit	Press fit	Press fit
Tibia	Tibia trough	Metal wire over cortical screw	Press fit	Screw/staple	IF screw	Bone bridge	Suture bone bridge	Press fit	Press fit	Suture bone bridge	IF screw	Suture bone bridge
Years FU	10.7	5 (36–62 m)	10.3 (9.6–10.8 years)	2.4 (22–41 m)	3 (24–77 m)	8.8	8.8	2.4 (20–40 m)	7 (5.3–7.5 years)	12.4 (12–14)	15	1
N=	95	93	148	42	285	28	25	40	152	106	52	30
Age	42	38.2	40.2	26 (21–46)	29.1	29.9 (25–55)	34.2 (26–64)	30 (16–54)	37.9	30 (18–45)	28 (16–43)	31 (16–47)
IKDC subj A/B	95 %		96 %					87, 50 %	98 %		77 %	86, 10 %
IKDC obj A/B	98 %		95 %						96 %			96, 70 %
IKDC gesamt A/B	84 %	57 %	87 %	88 %	84 %	84 %	94.40 %		89 %	86 %		
KT 1000/digital Rolimeter, mm	11 %		1.42 mm (±0.88)		1.91 mm (±2.1)			1.3 mm (±2. 2)	1.12 mm (±0. 72)	1.36 mm (±0.9)		1.6 (±1.1)
Lachman A 0–2, 9 mm	69 %	32 %	97 %	95.20 %		95 %	91.70 %		97 %	83 %		83 %
B 3–5, 9 mm	51 %	43 %	3 %	4.80 %					3 %	17 %		3.30 %
Pivot shift neg.	90 %	67 %	90 %						90 %			86.70 %
Glide	7 %	35 %	7 %						8 %			

	Hertel	Gobbi et al.	Felmet	Al-Husseiny et al.	Pavlik et al.	Wipfler et al.	Wipfler et al.	Halder	Felmet	Barie et al.	Widuchoswski et al.	Akoto et al.
Lysholm	93 %				93.5	87.28		91.82		88.5 (±12.7)	86.4	
Tegner activity												
Pretrauma	6.8		6.9						7.1			
Follow-up	6	7	5			6.2	6.14		5.5	6	6.9	86.7 % same as before
Complications			Tibia loosening 1, femur loosing 1, infection 3, fracture 0	Infection 1				Extension deficit 1, tibia fracture 1, patellar fracture 1, infection 1	Tibia loosening 1, femur loosing 1, infection 1, fracture 0	Rerupture 1, extension deficit >5° 1, flexion deficit >5° 1		Extension deficit 1
Osteoarthritis. fem. pat.	31 %		33 %						24 %			10 %
Osteoarthritis gap increasing	45 %	17 %	27 %						22 %			

tion in different diameters. This was the first time that it was possible to harvest the bone-tendon-bone patellar ligament with different diameters of bone cylinders with a hollow milling cutter system. Currently, we use sharper crown cutter as hollow reamer, which produces less heat and has low-priced disposables.

The patellar bone half cylinder has a diameter of 9 mm. This bone cylinder at the central third of the patellar tendon is given into the 11 mm hollow reamer. The complete graft is harvested with a diameter of 9 and 11 mm bone cylinder on each side (Fig. 24.1). The tibial 8–9 mm and femoral 9.5 mm tunnels are made with hollow reamers (Fig. 24.2). K-wire guiding devices can be used with a central adapter. Special guiding devices with tubes for hollow reamer have been developed for precise and reliable positioning of the tunnels. The femoral guide is placed with the longer tip behind the femoral condyle in 9:30 or 2:30 o'clock. The correct position in the original insertion is proved through the anteromedial portal. It should overlap the intermediate ridge between AM and PL bundle. Diameter can be measured by a ruler and be chosen up to 11 mm in larger knee for individual reconstruction. The tibial tube guide is positioned in the original insertion. Depending on the graft size, an 8 or 9 mm tibia tunnel is milled.

As opposed to common fixation, the graft is implanted from distal to proximal. We turned the common procedure upside down to the "bottom to top" (BTT) implantation (Fig. 24.4).

24.4.1.1 Bottom To Top (BTT) Fixation

First the graft is fixed press fit with the tibial bone cylinder near the joint. At a 120° knee flexion, the 9 mm bone cylinder from the patellar is inserted with the ligament into the femoral tunnel and pressed in. The bone cylinder from this tunnel fixes the ligament near the joint (Fig 24.4).

24.4.2 Hamstring

Based on this method, we developed a technique for hamstring graft in 2003.

Semitendinosus and gracilis tendon are harvested. For a diameter about 8 mm and length of 70 mm, semitendinosus or both tendons (if needed) are folded three or four times.

The femoral tunnel is drilled with the guiding device in the anatomical insertion with a 9 mm standard and can be individually enlarged up to 11 mm. The tibial tunnel is drilled by the tibial guiding device with the grafts size of 8 or 9 mm. Two bone cylinders (femur + tibia) are harvested.

The three or four strand hamstring graft is marked at the femoral end with a suture at 10 mm (for minimum depth in the femoral tunnel). In a distance from 3 to 4 cm, a 10 mm-long bone cylinder from the tibial tunnel is sutured into the graft (Fig. 24.5).

In a BTT (bottom to top) fixation, the graft is inserted from distal to proximal and first fixed directly under the tibial plateau press fit with the 11 mm bone cylinder. The proximal graft is pulled into the femoral tunnel and fixed with the 8–11 mm bone cylinder (harvested from this tunnel) in 120° knee flexion. The diameter depends on the individual size of the knee. The intermediate ridge has to be overlapped anterior and posterior. The bone cylinder press-fit fixation forms a crescent shape to imitate the AM and PL bundle (Fig. 24.8). The tunnel is closed with the bone cylinder from this tunnel (Fig. 24.4).

Similar principles can be applied for PCL reconstruction using press-fit hamstring autograft (Fig. 24.7). A secondary fixation in the manner of suture over a cortical bridge can be used, if bone quality is less than ideal.

24.4.3 Quadriceps Tendon (QT)

Quadriceps tendon was used in the past for revision cases. Today we also use it in primary ACL reconstruction. The mid third of the quadriceps tendon (QT) is harvested in a size of 10 mm width and 4–6 mm thick and a length of 80 mm. An attempt is made not to open the knee joint. A half bone cylinder can be harvested with a hollow reamer (crown cutter, micro crown cutter, or diamond miller) from the proximal patellar connected with the tendon. The bone cylinder can be harvested with an inclined cut from distal on to the QT. To receive a BTB graft, an 11 mm bone cylinder is harvested from the medial tibia and

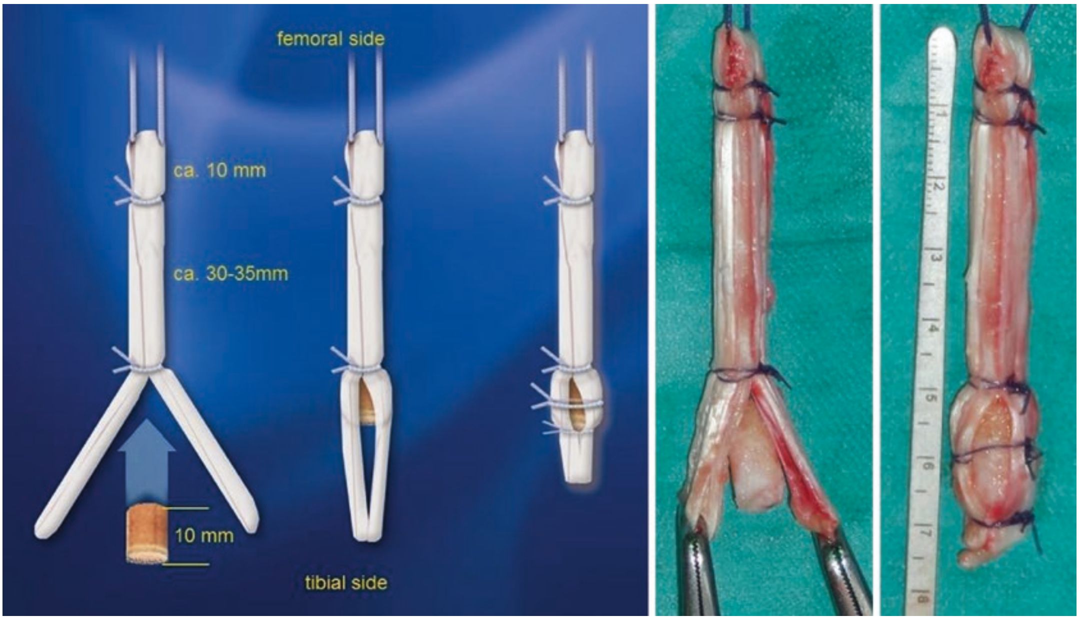


Fig. 24.5 Hamstring graft: the femoral side suture indicates the minimum length in the femoral tunnel. The tibial side sutures keep the tibial bone cylinder. With two sack and one trans-osseous sutures. The bone window is needed for bone-bone healing

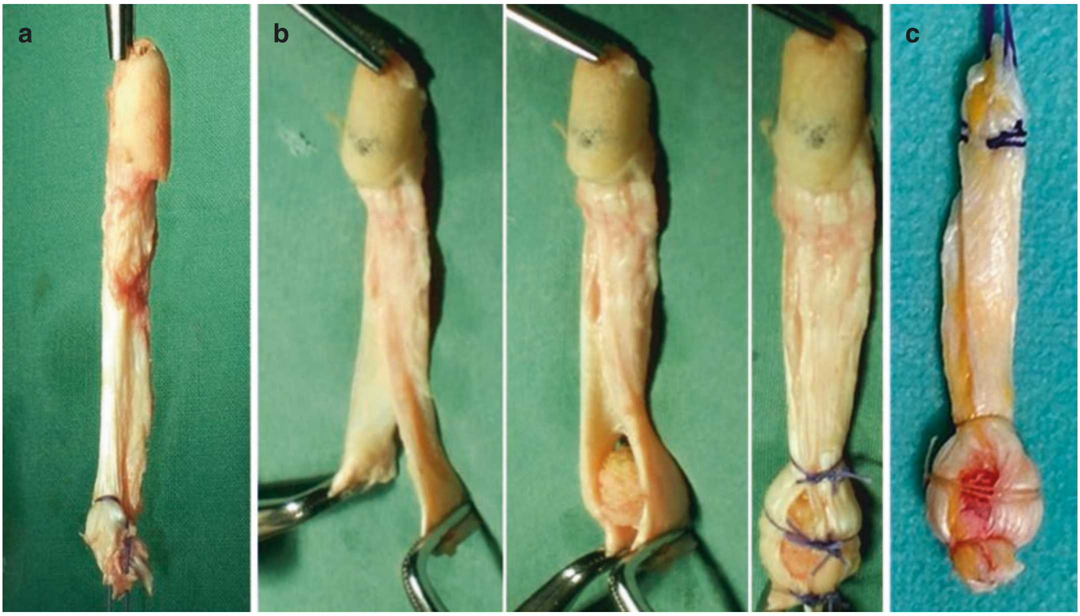


Fig. 24.6 The quadriceps tendon is harvested from the central third and the anterior 2/3 of the quadriceps tendon with a width of 8–10 mm and a length of about 70 mm. Adherent on the ligament, a “half bone cylinder” can be harvested with a hollow miller (**a**). An 11 mm bone cylinder from the tibial head analogue of the hamstring graft can be sutured in the proximal bisected quadriceps tendon for a bone-tendon-bone graft (**b**) or is only used in this way while harvested without patellar bone cylinder (**c**). Implantation follows analogue Fig. 24.4

sutured in the bifurcated proximal QT, which is analogous to the preparation of the hamstring graft. This can be particularly helpful in revisions. In primary reconstruction, we prefer the

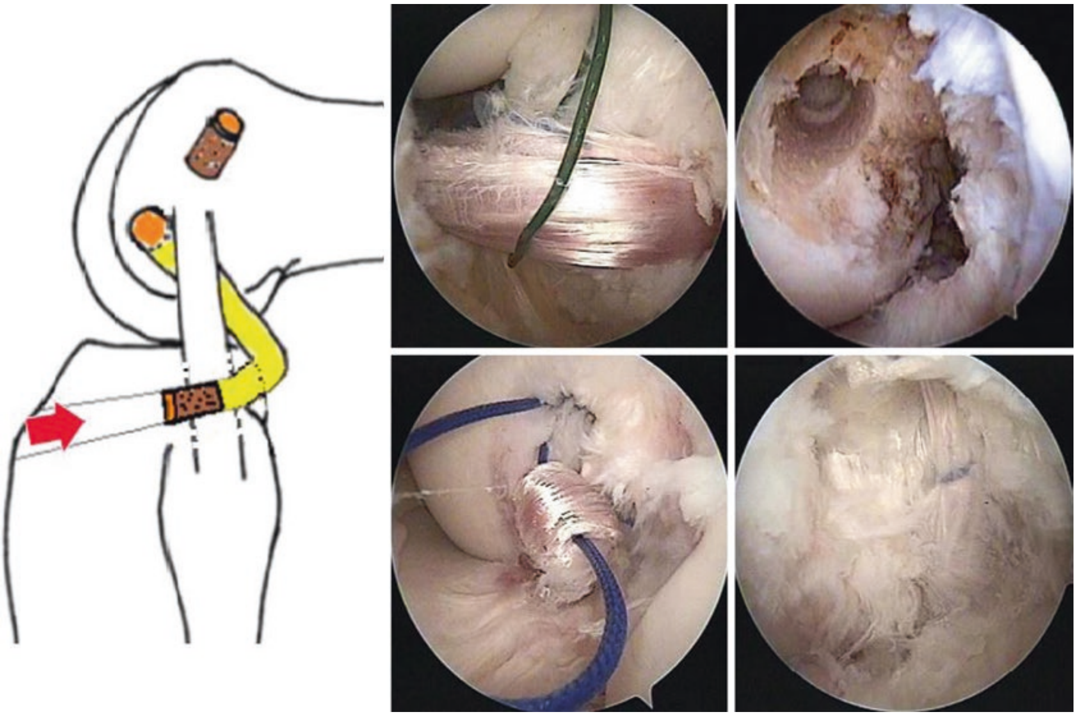


Fig. 24.7 PCL is reconstructed with hamstring prepared with the bone dowel from the tibial tunnel (Fig. 24.5) and fixed press fit at the posterior tibial head. The graft is implanted through a tibial tunnel, cashed and pulled forward into the anteromedial tunnel, and fixed with a bone cylinder. A suture over a bone bridge at the medial femoral condyle is necessary

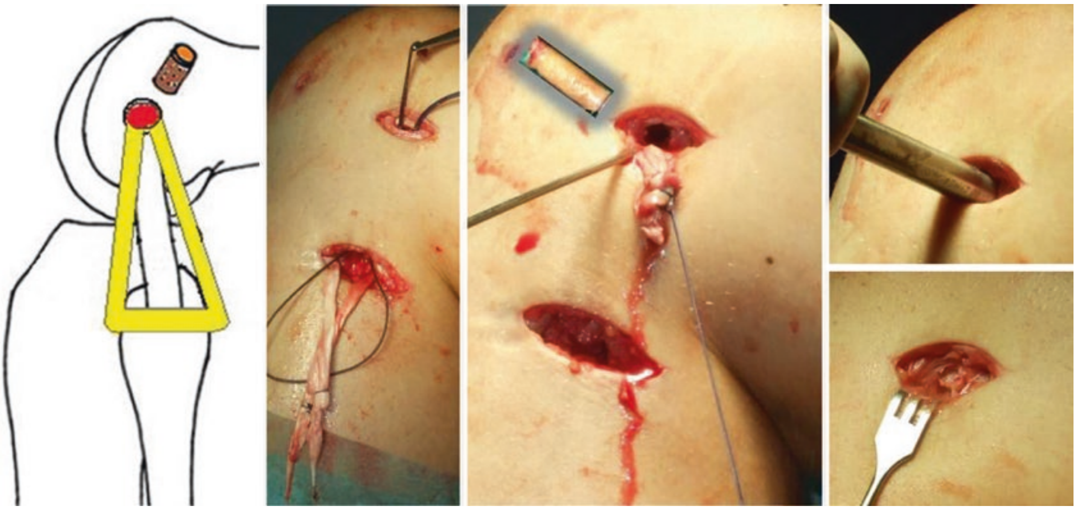


Fig. 24.8 A hamstring tendon is guided through a tunnel of the prox. fibula head and fixed press fit in femoral anchorage with the bone dowel from this tunnel. A suture over a bone bridge at the medial femoral condyle is necessary

free QT graft and use the bone cylinder from the proximal tibia (Fig. 24.6). Implantation is done in the BTT fixation with self-adapted tensioning (Fig. 24.4).

24.4.4 Revision

Bone plug fixation can be performed for revision surgery as well, usually as a single-stage revision surgery. After rerupture of a press-fit ACL reconstruction, a second reconstruction can be performed with a remaining graft on this side in the same technique [39]. Based on the tunnel size, different diameters of bone cylinders can be harvested (Fig. 24.2). Sizes up to 19 mm cortical-cancellous bone cylinders have been harvested from the proximal tibia and were sutured to the tibial side of the graft. The enlarged tunnel is closed and the graft is fixed in one stage. The femoral tunnel fixation is treated in the same way (Fig. 24.10) [35].

24.4.5 Other Ligaments Reconstruction

PCL, LCL, MCL, and MPFL reconstructions are performed in the same method of a ligament-bone plug press-fit fixation. Because of lower bone stability, it is helpful to add a suture over a bone bridge at the femoral side of fixation for many of these [36] (Figs. 24.7, 24.8, and 24.9).

24.5 Clinical Outcome

Twelve studies report a total of 1,096 individuals with device-free, press-fit fixation [5, 8–10, 14, 19, 37, 38, 40–42] (Table 24.1). Results overall have been good to excellent. Four cases of bone block loosening without clinical relevance were described [37, 40]. Patellofemoral crepitus was noted in 10–40 % cases. Long-term radiological signs of osteoarthritis were observed in 17–45 % and were more common in patients who had concomitant partial meniscectomy [5, 10, 37, 40, 41].

24.6 Discussion

For accelerated rehabilitation, the initial fixation strength should be strong enough to counteract the resultant forces. Full extension of the knee by contraction of the quadriceps muscle has been shown to produce forces up to 200 N on the ACL graft [43]. Press-fit fixation for hamstring on both sides has the stability of about 300 N at the tibial anchorage [44]. Early functional rehabilitation is started in the postoperative period. The lower graft stability of hamstring in the first 6 weeks has to be accounted for in the rehabilitation program [45].

Fig. 24.9 A hamstring tendon is guided through a tunnel of the medial patellar and fixed press fit in a femoral anchorage with the bone dowel from this tunnel. The lateral quadriceps tendon analogous can be used. A suture over a bone bridge at the lateral femoral condyle is necessary

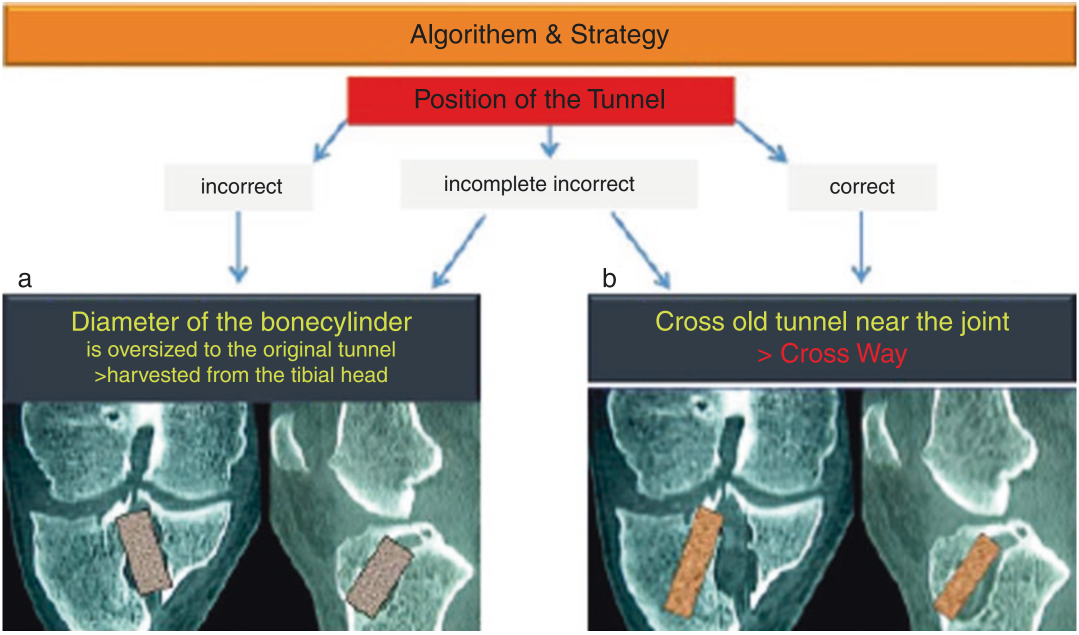


Fig. 24.10 The strategy in revision offers (**a**) the use of a bone cylinder from the tibial head only – in a diameter “plus 1 mm” of the old tunnel – to fix the graft and close the defect in one step. (**b**) The “crossway” uses a different tunnel to avoid the first tunnel

Free range of movement is allowed from day 1 in individuals with good bone quality. In cases where bone quality is questionable, we limit extension/flexion in 0-20-90 for 3 weeks in a brace. A brace is given for 4–6 weeks and full weight bearing is possible at 1 week postoperatively. We have shown beneficial effects of aquasprint [46] and proprioceptive vibration training on the quadriceps muscle as part of rehabilitation [47]. Proprioceptive vibration training (Powerplate assisted proprioception training is started at 3 weeks post surgery) is used after 3 weeks post-op two times a week. We suggest undertaking clinical measurements of anterior stability with tools like digital Rolimeter and muscle function tests after 3 months [46–48].

Most of the biomechanical studies are performed on porcine, bovine, or cadavers, which exhibit different osseous properties. Porcine or goats have thick nonelastic cortical bone but no cancellous bone. Human bone cylinder has stiff cortical bone and elastic cancellous bone. The behavior of viscoelastic strain and deformation can be observed in the fresh harvested cortical-cancellous bone cylinder. Cancellous bone swells after harvesting and increased bone diameter can be noted when it is ready for impaction into the tunnel. A similar viscoelastic deformation occurs after press-fit fixation inside the tunnel – which enhances fixation after implantation [37, 40, 41].

Direct bone contact is necessary for secure biological integration of press-fit fixation, which takes around 4–6 weeks [49]. It contributes to rapid and stable graft healing. If bone contact is lacking, atrophy of the tibial bone cylinder can be observed. This technique also involves fixation of graft close to tunnel entrance. It has multiple advantages. It avoids “bungee effect,” whereby graft moves longitudinally within the tunnel because fixation is away from the tunnel entrance. It also prevents synovial fluid entering the tunnel, hence avoiding possible negative effects of cytokines [50]. A broad anatomic femoral insertion with autogenous bone plugs inserted near the cortex seems to improve rotational stability [51, 52].

As with other fixation methods, press-fit fixation is adaptable to different graft types with good results. Latest reports of press-fit hamstring vs quadriceps tendon demonstrated similar stability and muscle strength compared to the noninjured side [53]. In a 10-year prospective analysis, no significant difference in stability was observed between press-fit quadriceps tendon vs patellar BTB [54].

There are two main issues, which makes revision ACL reconstruction quite challenging, i.e., removal of primary fixation device and dealing with dilated tunnels. With press-fit fixation, both these issues are avoided. If tunnel widening is encountered, different diameter harvesters can be very useful. A bigger bone cylinder can be harvested from the tibia and a dilated tunnel can be obliterated, making it possible to do the procedure in single stage. A crossing tunnel technique has also been described [35] (Fig. 24.10).

A limitation of this technique is the technically demanding nature of the procedure as tunnel-graft size mismatch can lead to inadequate fixation and subsequent failure. Use of different sized reamers and tunnel compaction has made the procedure more precise and reproducible. The other problem is inadequate fixation in patients with osteoporotic bone, where secondary fixation might be required.

Using this technique, posterior cruciate ligament (PCL), lateral collateral ligament (LCL), medial collateral ligament (MCL), and the medial patellar-femoral ligament (MPFL) are reconstructed in a biological manner. The bone dowels, which are harvested out of the tunnels, are used for fixing the graft in a press-fit manner. Sutures over a bone bridge are suggested at anchorage in mid or anterior femoral condyle in cases of soft bone and/or cases with less primary press-fit bone cylinder stability.

Conclusion

Press-fit fixation has been around for more than 25 years. It provides undisturbed bone-to-bone healing and avoids any problems associated with hardware fixation, such as graft laceration, biocompatibility, biodegradability, and local reactions leading to tunnel enlargement. A growing number of sports injuries and reruptures have led to financial pressures on health-care systems and insurances. An incentive by a one German insurance company has been offered for biological fixation since 2015. Knee surgeons should understand the principles and techniques that make implants in ligament surgery nonessential.

Take-Home Message

Pros:
- Biological approach
- Anatomical and individual insertion
- No implant-related complications
- Cost-effective
- Decreased risk of tunnel widening
- No signal interference during follow-up MR imaging
- Relatively less challenging revision reconstruction

Cons:
- Modified rehabilitation in osteopenic bone and need for secondary fixation in PCL, LCL, and MPFL
- Conflict of interest: none

References

1. Brown CH Jr, Carson EW (1999) Revision anterior cruciate ligament surgery. Clin Sports Med 18:109–171
2. Pinczewski LA et al (2007) A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. Am J Sports Med 35(4):564–574
3. Dargel J et al (2006) Biomechanical testing of quadriceps tendon-patellar bone grafts: an alternative graft source for press-fit anterior cruciate ligament reconstruction? Arch Orthop Trauma Surg 126(4):265–270
4. Hertel P (1990) Anatomic reconstruction of the ACL: a new technique for ACL replacement, in 4th ESSKA Congress. Stockholm
5. Hertel P et al (2005) ACL reconstruction using bone-patellar tendon-bone press-fit fixation: 10-year clinical results. Knee Surg Sports Traumatol Arthrosc 13(4):248–255
6. Hertel P, Behrend H (2010) Implant-free anterior cruciate ligament reconstruction with the patellar ligament and press-fit double bundle technique. Unfallchirurg 113(7):540–548

7. Boszotta H (1997) Arthroscopic anterior cruciate ligament reconstruction using a patellar tendon graft in press-fit technique: surgical technique and follow-up. Arthroscopy 13(3):332–339
8. Barie A et al (2010) Anterior cruciate ligament reconstruction using quadriceps tendon autograft and press-fit fixation. Unfallchirurg 113(8):629–634
9. Akoto R, Hoeher J (2012) Anterior cruciate ligament (ACL) reconstruction with quadriceps tendon autograft and press-fit fixation using an anteromedial portal technique. BMC Musculoskelet Disord 13:161
10. Gobbi A et al (2002) Patellar tendon anterior cruciate ligament reconstruction with conical press-fit femoral fixation: 5-year results in athletes population. Knee Surg Sports Traumatol Arthrosc 10(2):73–79
11. Felmet G (1999) ALL-PRESS-FIT a new surgical method with femoral and tibial Press Fit fixation. Arthroskopie 12:299–304
12. Felmet G (1997) [ACL Reconstruction with the central third of the patellar ligament and simultaneous proximal and distal press fit fixation, ALL PRESS FIT] in 14. Kongress der deutschsprachigen Arbeitsgemeinschaft für Arthroskopie AGA, AGA, Editor, Berlin
13. Felmet G (2000) ACL Reconstruction with proximal and distal press fit fixation (ALL PRESS FIT) with SDI (Surgical Diamond Instrument) Instruments. Osteosynthese Int 8(Suppl 1):173–174
14. Halder AM, Ludwig S, Neumann W (2002) Arthroscopic anterior cruciate ligament reconstruction using the double press- fit technique: an alternative to interference screw fixation. Arthroscopy 18(9):974–982
15. Paessler HH, Mastrokalos DS (2003) Anterior cruciate ligament reconstruction using semitendinosus and gracilis tendons, bone patellar tendon, or quadriceps tendon-graft with press-fit fixation without hardware. A new and innovative procedure. Orthop Clin North Am 34(1):49–64
16. Liu YJ et al (2005) The clinical application and biomechanical study of reconstruction of anterior and posterior cruciate ligament with hamstring tendons knot implant fixation. Zhonghua Wai Ke Za Zhi 43(4):239–242
17. Felmet G (2004) [ALL PRESS FIT, a near the origin ACL Reconstruction with Semitendinosus & Gracilis Tendon, a New Surgical Technique] in 21. Kongress der deutschsprachigen Arbeitsgemeinschaft für Arthroskopie (AGA). Luzern, Switzerland
18. Felmet G (2011) Anatomic double bundle single tunnel foreign material free ACL-reconstruction – a technical note. Muscles Ligaments Tendons J 1(4):148–152
19. Al-Husseiny M, Batterjee K (2004) Press-fit fixation in reconstruction of anterior cruciate ligament, using bone-patellar tendon-bone graft. Knee Surg Sports Traumatol Arthrosc 12(2):104–109
20. Prado RK et al (2012) A new technique in double-bundle anterior cruciate ligament reconstruction using implant-free femoral fixation. Int Orthop 36(7):1479–1485; discussion 1539–41
21. Rupp S, Krauss PW, Fritsch EW (1997) Fixation strength of a biodegradable interference screw and a press-fit technique in anterior cruciate ligament reconstruction with a BPTB graft. Arthroscopy 13(1):61–65
22. Musahl V et al (2003) Tensile properties of an anterior cruciate ligament graft after bone-patellar tendon-bone press-fit fixation. Knee Surg Sports Traumatol Arthrosc 11(2):68–74
23. Seil R et al (1998) Comparison of initial fixation strength between biodegradable and metallic interference screws and a press-fit fixation technique in a porcine model. Am J Sports Med 26(6):815–819
24. Lee MC et al (2003) Analysis of initial fixation strength of press-fit fixation technique in anterior cruciate ligament reconstruction. A comparative study with titanium and bioabsorbable interference screw using porcine lower limb. Knee Surg Sports Traumatol Arthrosc 11(2):91–98
25. Kuhne JH, Fottner M, Plitz W (1999) Experimental stability of a new implant-free fixation technique in ACL replacement. Unfallchirurg 102(10):791–796
26. Mayr HO et al (2005) Axial load in case of press-fit fixation of the ACL graft – a fundamental study. Z Orthop Ihre Grenzgeb 143(5):556–560
27. Schmidt-Wiethoff R et al (2006) Bone plug length and loading angle determine the primary stability of patellar tendon-bone grafts in press-fit ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 14(2):108–111
28. Pavlik A et al (2004) Biomechanical evaluation of press-fit femoral fixation technique in ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 12(6):528–533
29. Dargel J et al (2007) The effect of bone tunnel dilation versus extraction drilling on the initial fixation strength of press-fit anterior cruciate ligament reconstruction. Arch Orthop Trauma Surg 127(9):801–807
30. Kilger RH et al (2005) The effectiveness of reconstruction of the anterior cruciate ligament using the novel knot/press-fit technique: a cadaveric study. Am J Sports Med 33(6):856–863
31. Boszotta H, Anderl W (2001) Primary stability with tibial press-fit fixation of patellar ligament graft: an experimental study in ovine knees. Arthroscopy 17(9):963–970
32. Jagodzinski M et al (2006) Tibial press-fit fixation of the hamstring tendons for ACL-reconstruction. Knee Surg Sports Traumatol Arthrosc 14(12):1281–1287
33. Ettinger M et al (2012) Tibial press-fit fixation of flexor tendons for reconstruction of the anterior cruciate ligament. Unfallchirurg 115(9):811–815
34. Ettinger M et al (2012) The fixation strength of tibial PCL press-fit reconstructions. Knee Surg Sports Traumatol Arthrosc 20(2):308–314
35. Felmet G (2010) [ACL Revision material free in a single step], in 25th annual meeting of GOTS. Munich
36. Felmet G (2008) Ligament surgery – when do we need it and when not. 57th annual meeting of the North German Orthopedic Society, June 12–14 2008, Hamburg

37. Felmet G (2010) Implant-free press-fit fixation for bone-patellar tendon-bone ACL reconstruction: 10-year results. Arch Orthop Trauma Surg 130(8):985–992
38. Pavlik A et al (2006) Femoral press-fit fixation technique in anterior cruciate ligament reconstruction using bone-patellar tendon-bone graft: a prospective clinical evaluation of 285 patients. Am J Sports Med 34(2):220–225
39. Wipfler B et al (2011) Anterior cruciate ligament reconstruction using patellar tendon versus hamstring tendon: a prospective comparative study with 9-year follow-up. Arthroscopy 27(5):653–665
40. Felmet G (2013) Foreign material-free ACL reconstruction with hollow miller: a biological and anatomic method for every ligament. Tech Orthop 28(2):166–175
41. Felmet G (2010) Implant-free anterior cruciate ligament reconstruction with diamond instruments. A biological and anatomic method for every ligament transplantation. Unfallchirurg 113(8):621–628
42. Widuchowski W et al (2012) Femoral press-fit fixation in ACL reconstruction using bone-patellar tendon-bone autograft: results at 15 years follow-up. BMC Musculoskelet Disord 13:115
43. Engebretsen L et al (1989) Knee mechanics after repair of the anterior cruciate ligament. A cadaver study of ligament augmentation. Acta Orthop Scand 60(6):703–709
44. Siebold R et al (2008) Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: morphometry and arthroscopic orientation models for double-bundle bone tunnel placement – a cadaver study. Arthroscopy 24(5):585–592
45. Tomita F et al (2001) Comparisons of intraosseous graft healing between the doubled flexor tendon graft and the bone-patellar tendon-bone graft in anterior cruciate ligament reconstruction. Arthroscopy 17(5):461–476
46. Felmet G (2002) [“Aquasprint” in the early functional rehabilitation program after ACL reconstruction] Arthroskopische Gelenkchirurgie, Gestern-Heute-Morgen, Standortbestimmunged. Frenzel G, Wuschech H (eds). Kongress Compact Verlag, Berlin, pp 188–196
47. Felmet G (2004) [The significance of Proprioceptive Vibration Training in postoperative treatment after ACL Reconstruction], in DGOOC, Berlin
48. Krautter A, RL, Moeller K, Zhao Z, Felmet G, Instrumented Arthrometry of the anterior cruciate ligament. A comparison. Biomed Tech (Berl), 2012(issue-s1-R/bmt-2012-4299/bmt-2012-4299)
49. Dargel J et al (2005) Histomorphology and microradiography of quadriceps tendon-patellar bone grafts in press-fit anterior cruciate ligament reconstruction. J Orthop Res 23(5):1206–1210
50. Cameron M et al (1997) The natural history of the anterior cruciate ligament-deficient knee. Changes in synovial fluid cytokine and keratan sulfate concentrations. Am J Sports Med 25(6):751–754
51. Jarvela T et al (2008) Double-bundle anterior cruciate ligament reconstruction using hamstring autografts and bioabsorbable interference screw fixation: prospective, randomized, clinical study with 2-year results. Am J Sports Med 36(2):290–297
52. Muneta T (2015) Twenty-year experience of a double-bundle anterior cruciate ligament reconstruction. Clin Orthop Surg 7(2):143–151
53. Horstmann H, Felmet G, Tegtbur U, Krettek C, Jagodzinski M (2014) Influence on graft choice between Hamstring and Quadriceps Tendon on muscle function in implant free ACL Reconstruction, in DKOU, Berlin
54. Barié A, Huber J, Streich NA (2012) Implant-free replacement of the anterior cruciate ligament – quadriceps tendon versus patellar tendon – long-term results of a prospective randomized clinical study. Knee Surg Sports Traumatol Arthrosc 20(Suppl 1):34

Is Notchplasty Necessary for Anatomic ACL Reconstruction?

25

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25.1 Introduction

The terms notchplasty, wallplasty, and roofplasty refer to the removal of bone from the lateral margin or roof of the femoral intercondylar notch during anterior cruciate ligament (ACL) reconstruction (Fig. 25.1). Classic papers from the 1980s by Feagin et al. [2], Kieffer et al. [3], and Odensten and Gillquist [4] were among the earliest studies to recommend notch enlargement as a routine step in ACL reconstruction. The purpose of notchplasty was to prevent graft impingement, improve visualization, and facilitate graft passage. Kieffer et al. [3] also hypothesized that the exposed cancellous surface following "arthroplastic relief of the lateral femoral condyle" may facilitate graft vascularization and early healing. Over the following decades, as surgical techniques evolved with an increased emphasis on "anatomic" ACL reconstruction, surgeons began to investigate whether notchplasty was necessary or even detrimental. These newer techniques had to address how to achieve the purported benefits of notchplasty without altering the bony morphology of the intercondylar notch. The purpose of this chapter is to address how issues regarding the intercondylar notch relate to ACL reconstruction and whether notchplasty is necessary for anatomic ACL reconstruction.

25.2 Indications for Notchplasty and Notchplasty Technique

For many years, nonanatomic "isometric" ACL reconstruction was the standard of care. The predominant reasons for employing this technique included the technical ease of the arthroscopic transtibial approach and the avoidance of graft impingement (Fig. 25.2). Concerns regarding graft impingement were based on the observation that the ACL impinged upon the anterior intercondylar notch when the knee was brought into full extension and failed when the knee was forced into hyperextension [5]. Cadaveric studies found that contact pressure between a graft and the intercondylar roof increased during passive knee extension, that this pressure increased and occurred earlier in the knee flexion arc with active quadriceps loading, and that notchplasty

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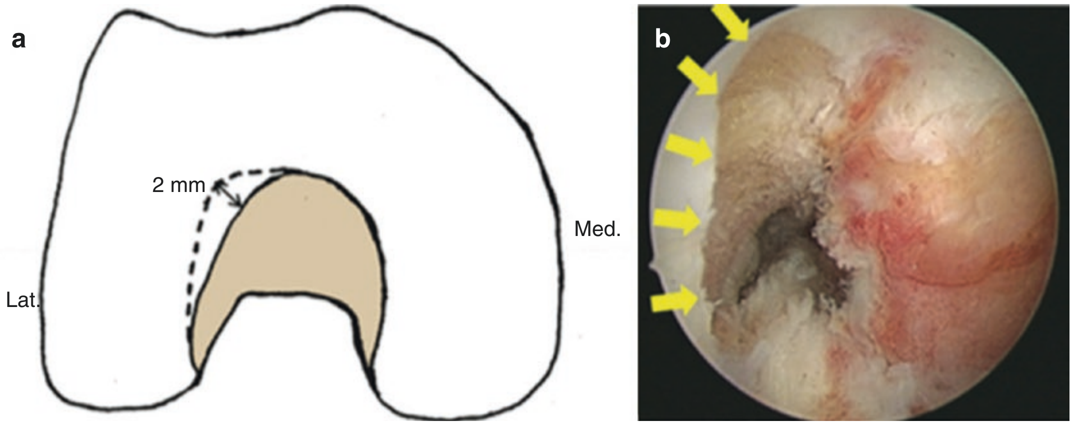

Fig. 25.1 Illustration and arthroscopic image showing a right knee notchplasty (Reprinted from Koga et al. [1], ©2014, by permission of SAGE Publications)

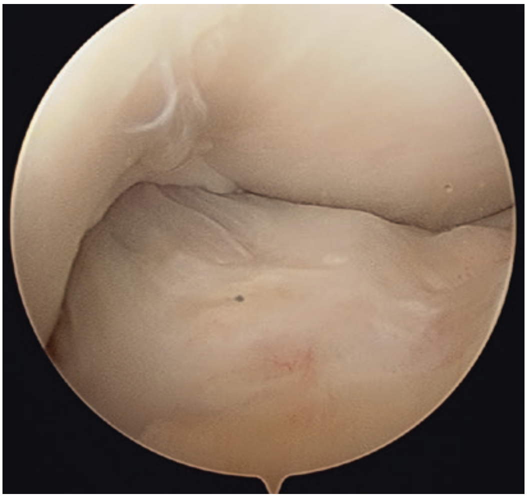

Fig. 25.2 Arthroscopic view of a right knee from the anterolateral portal showing the knee in full extension with intercondylar notch impingement of the ACL graft following primary reconstruction without notchplasty

reduced the contact pressure and flexion arc over which impingement occurred [6–10]. ACL impingement can also occur with tibial external rotation and abduction, as may be the case during noncontact injuries when the foot lands or is planted [11]. The detrimental effects of graft impingement were reinforced by studies showing a significant relationship between graft impingement and anterior knee pain, effusions, instability, extension deficit, increased graft signal on magnetic resonance image (MRI), and potential graft failure [12–15].

Parallel studies noted significant associations between narrower notch morphology and the risk or incidence of ACL injury [16–27]. A level-III meta-analysis concluded that lower intercondylar notch width index (NWI) or intercondylar notch width (NW) is a predisposing factor to ACL injury [28]. However, other studies failed to corroborate a significant association between notch measurements and ACL injury [29–33]. For example, Al-Saeed et al. [34] found that a type A notch correlated with ACL injury but NWI did not. Conversely, Ireland et al. [35] found that notch shape was not related to ACL injury status, whereas reduced NWI and NW were significant risk factors. The work of van Eck et al. [36] found that three-dimensional notch volume was greater in patients with ACL injuries compared with controls but that it did not correlate with intraoperative two-dimensional notch measurements. These differing results may be in part due to the variability between studies regarding the type and method of notch measurements as various distances, angles, and ratios have been described to quantify notch morphology. Other potential confounding factors include gender, tibial plateau slope, native ACL morphology compared with graft morphology, and whether a smaller notch itself is not a causative factor for ACL injury but rather a surrogate indicator of a smaller and potentially weaker ACL [21, 37–39]. Despite inconsistent results in the literature, most surgeons believe that some relationship exists between notch morphology and ACL injury.

Citing these studies that identified significant relationships between notch morphology, graft impingement, and ACL/graft injury, authors continued to advocate notchplasty and/or posterior tunnel placement during ACL reconstruction [12–17, 40–44]. Howell and Barad [41] found that the "unforgiving knee" – a knee that hyperextends and has a vertically oriented slope of the intercondylar notch – requires a posteriorly positioned tibial tunnel and extensive notchplasty to avoid impingement. Tanzer and Lenczner [43] agreed that notch stenosis was an indication for notchplasty but also argued that a graft ≥8 mm would impinge in a nonstenotic notch and recommended notchplasty in such circumstances.

The recommended notchplasty size varies in the literature. Most recommendations range 2–6 mm, while an early technique by Magill [45] recommended removing 30 % the lateral femoral condyle [46–50]. Odensten and Gillquist [4] measured the notch width to be 21 ± 3 mm in normal cadaveric knees and thus recommended notchplasty to recreate this width during ACL reconstruction. To avoid graft–roof contact throughout range of motion, Berns and Howell [10] found that a 4.6 ± 1 mm roofplasty was required with anterior/eccentric tibial tunnel placement and that 1.3 ± 1.1 mm roofplasty was required with a tibial tunnel oriented 4–5 mm posterior and parallel to the intercondylar roof. Zuiderbaan et al. [51] evaluated anterior tibial translation (ATT) and ligament impingement in four states: intact ACL, acute ACL disruption, chronic ACL disruption, and failed ACL reconstruction. The authors found that as ATT varies among states, so too does the volume and location impingement. They concluded that the volume and location of notchplasty should depend on the specific pathoanatomy being addressed.

To evaluate tunnel position, detect impingement, and determine the need for or size of notchplasty, some surgeons suggested inserting an impingement rod or drill with the same diameter as the proposed graft through the tibial tunnel and intercondylar notch [15, 52–54]. With the knee in maximum extension, notchplasty was recommended if the rod became obstructed but not if it passed easily and without impingement.

Repeat notchplasty at second-look arthroscopy has also been described to address delayed impingement between the ACL graft and intercondylar notch following ACL reconstruction [52, 55–57]. A study by Lane et al. [56] included six patients with a symptomatic knee "thunk" on active extension following ACL reconstruction. At an average of 5 months following the onset of symptoms, arthroscopy found anterior and/or lateral graft–notch impingement in all patients and partial graft tearing at the site of impingement in three patients. All patients had resolution of symptoms following notchplasty. An MRI study of 21 patients following repeat notchplasty found continued graft high-signal intensity in 12 patients and decreased signal intensity in 9 patients [55].

25.3 Effects of Notchplasty

25.3.1 Notch Reformation

The prevalence of notch reformation varies in the literature (Fig. 25.3). In a rabbit model, gross and histologic examination found that exposed cancellous bone at the notchplasty site became covered with fibrous scar tissue, but no osteochondral reconstitution occurred in any specimen [46]. Other animal studies using canine models have found significant refilling of the notchplasty site with fibrous tissue, fibrocartilage, and bone [58, 59]. Clinical studies also have found variable results. A computed tomography (CT) study of patients who had 5-mm notchplasty found no significant differences in multiple notch measurements between 1 week and 1 year postoperatively [60]. During second-look arthroscopy after a mean of 21.2 months, Ahn et al. [61] found 1- to 3-mm notch reformation in 33 % of knees, >3-mm reformation in 7 %, and some degree of graft impingement in 26 % regardless of the graft type. On MRI 6 months after ACL reconstruction, including a 3- to 5-mm notchplasty, Bents et al. [62] found that 97 % of knees showed notchplasty site recortication and 49 % had regrowth of 2–3 mm but that clinical evidence of

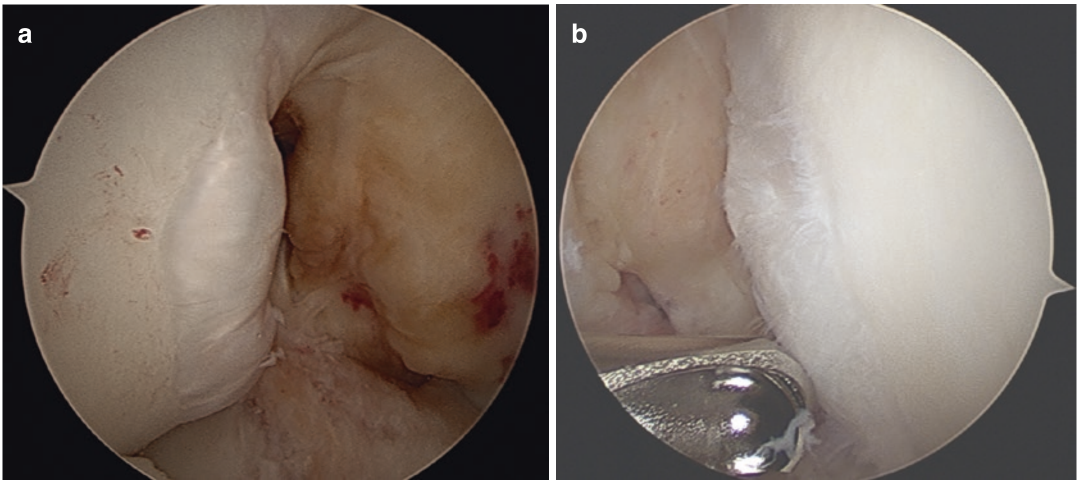

Fig. 25.3 Arthroscopic views of *right* (**a**) and *left* (**b**) knees from the anterolateral portals showing bony hypertrophy and fibrous tissue at the sites of previous notchplasty

graft impingement was found in smaller percentages of knees on MRI (22 %) or physical examination (11 %). Another MRI study reported that 6 months following notchplasty, 94 % of patients had 0.5- to 1.5-mm recortication overlying the notchplasty, site and 64 % of patients had a second 1- to 5-mm layer with signal intensity similar to that of hyaline cartilage [63]. While the biologic response to notchplasty appears variable, studies have consistently shown that native anatomy is not restored following notchplasty.

25.3.2 Patellofemoral Joint

The effect of notchplasty on the articular surfaces of the patellofemoral joint has also been investigated. Morgan et al. [64] measured patellofemoral contact areas and pressures in cadaveric knees and after 3-, 6-, and 9-mm notchplasties. There were no statistical differences between groups at 90°, 105°, and 120° of knee flexion. On the basis of these data, the authors suggested that notchplasty up to 9 mm may be performed without causing anterior knee pain or patellofemoral joint deterioration. Shino et al. [65] evaluated the patellofemoral articular surface at the time of ACL reconstruction and again during second-look arthroscopy at an average of 19 months later. They identified patellofemoral articular surface deterioration in 51 % (93/181) of knees. In the 101 patients who had arthroscopic reconstruction, the incidence of joint surface deterioration was 54 % (13/24) in patients who had notchplasty compared to 38 % (29/77) in those who did not undergo notchplasty. This difference was not statistically significant, and the authors concluded that a 4- to 6-mm notchplasty did not adversely affect the patellofemoral articular surface [65].

Animal studies have shown that an aggressive notchplasty may have an effect on patellofemoral articular cartilage. Using a canine model, LaPrade et al. [59] compared the effects of sham surgery, 4-mm notchplasty (correlating with a 6 to 8-mm notchplasty in humans), and 7 to 8-mm notchplasty (12 to 16-mm notchplasty in humans). Compared with the control group, at 6 months the notchplasty groups had macroscopic articular cartilage changes and significant loss of lateral femoral condyle and trochlear groove articular surface proteoglycans. The authors noted that these histopathologic changes of the articular cartilage were consistent with the changes seen in early degenerative osteoarthrosis. The authors recommended that notchplasty should be as limited as possible or not performed if avoidable. In a similar study using rabbits, Asahina et al. [46] compared patellar articular cartilage changes among a control group, a 1-mm notchplasty group (correlating with a 5-mm notchplasty in humans), and a 3-mm notchplasty group (15-mm notchplasty in humans). There were no microscopic differences between the control and 1-mm notchplasty groups; however, extensive articular deterioration was seen in the 3-mm notchplasty group. These findings were more common when notchplasty was performed in combination with bone–patellar tendon–bone autograft harvest. Despite these reports, there is a lack of high-quality evidence on the effect of notchplasty on patellofemoral articular cartilage in humans.

25.3.3 Blood Loss

There is little published data on notchplasty-associated blood loss. In a prospective clinical study, Pape et al. [66] found that notchplasty with a motorized burr resulted in significantly increased blood loss and decreased serum hematocrit compared to no notchplasty; however, there were no clinical differences between groups at 12 months postoperatively. Another study reported significantly less blood loss when notchplasty was performed with a radiofrequency device as opposed to a motorized shaver [67]. While increased intra-articular bleeding may promote fat pad fibrosis that could compromise range of motion, additional studies would be needed to determine the effect of blood loss from the notchplasty site [1, 68].

25.3.4 Knee Biomechanics

Markolf et al. [69] conducted the first study on the biomechanical effects of notchplasty. They found that 2- and 4-mm notchplasties resulted in abnormal graft laxity patterns, greater graft excursion, greater graft forces, and higher pretension requirements to restore normal laxity. In a porcine model, Keklikci et al. [70] compared the intact ACL, an ACL-deficient knee, anatomic single-bundle ACL reconstruction, and anatomic single-bundle ACL reconstruction with a 5-mm notchplasty. They found significant differences in the notchplasty group, including greater ATT at 30° and 60° of knee flexion; lower in situ graft force with ATT at 30°, 60°, and 90° of knee flexion; and greater internal rotation tibial torque at 60° of knee flexion. Hame et al. [48] conducted a cadaveric study to determine the effects of varying femoral tunnels before and after 2-mm notchplasty. They found no difference in bone–patellar tendon–bone graft excursions prior to notchplasty but significantly greater graft tightening during 20–90° of knee flexion for all femoral tunnel positions.

Seo et al. [71] used a porcine model to investigate the effects of notchplasty on femoral tunnel diameter and orifice area following ACL reconstruction with suspensory fixation and cyclic loading. In the notchplasty group following testing, there was significantly increased mean longest tunnel diameter, area of the intra-articular orifice, and volumetric bone loss at the anterior margin of the tunnel compared with before testing. In the non-notchplasty group, there were no significant differences in tunnel morphology before and after testing. The authors hypothesize that even with anatomic femoral tunnel placement, removing harder cortical bone during notchplasty exposes softer cancellous bone that may be more susceptible to deformation with cyclic loading. Such alterations in tunnel geometry could result in graft–tunnel mismatch and affect graft position, biomechanics, and laxity.

Fu et al. [72] argue that notchplasty laterally displaces the femoral graft insertion and can result in abnormal knee kinematics. Other studies agree with this hypothesis and contend that observed biomechanical differences may be due to altered tibial–femoral kinematics or because notchplasty recesses the femoral tunnel aperture, effectively altering tunnel length and/or graft length, orientation, loading, and function. Brown et al. [73] suggest that if notchplasty is required, it should be performed after femoral tunnel drilling to avoid lateral displacement of the femoral tunnel. In general, these studies conclude that as little bone as possible should be removed from the intercondylar notch during ACL reconstruction.

25.3.5 Clinical Outcomes

Koga et al. [1] conducted the first clinical study on the effect of notchplasty following anatomic double-bundle ACL reconstruction (Tables 25.1, 25.2, 25.3, and 25.4). They found significantly greater objective and subjective loss of extension in the notchplasty group, with six of those

Table 25.1 Demographic and preoperative data of patients

Parameters	Without NP	With NP	*P* value
Age at surgery (years) (average; range)	23 (14–48)	26 (14–56)	0.18
Gender, male/female	31/41	21/41	0.31
Pre-op period (month) (average; range)	23 (1–360)	28 (1–276)	0.44
Pre-op Tegner score (average; range)	7.0 (3–9)	6.9 (3–9)	0.48
KT-1000 arthrometer (mm) (average +/− SD)	6.8 ± 2.2	6.1 ± 2.0	0.10
Lachman test (number)			0.41
1+	5	1	
2+	56	57	
3+	11	3	
Anterior drawer test (number)			0.64
1+	30	26	
2+	38	35	
3+	4	0	
Pivot-shift test (number)			0.18
1+	4	5	
2+	57	54	
3+	11	2	
Combined meniscal injuries (number)	37	20	0.031
MM (repair, partial removal)	22 (21, 1)	10 (8, 2)	
LM (repair, partial removal)	15 (11, 4)	10 (7, 3)	

Table 25.2 Clinical findings and evaluation at 2-year follow-up

Parameters	Without NP ($n = 72$)	With NP ($n = 61$)	*P* value
Thigh girth (cm) (Average ± SD)	0.5 ± 1.1	0.6 ± 1.0	0.87
Patellofemoral pain (number)			0.69
Negative	68	59	
Positive	4	2	
Patellofemoral crepitation (number)			0.99
Negative	70	59	
Positive	2	2	
Post-op. knee laxity results			
KT measurements (mm) (average ± SD)	1.2 ± 1.3	0.4 ± 1.3	0.0017
KT measurements < −2 mm (number)	1	6	0.048
Lachman test (number)			0.55
Negative	68	56	
1+	4	5	
Anterior drawer test (number)			0.13
Negative	63	58	
1+	9	3	
Pivot-shift test (number)			0.98
Negative	56	48	
1+	16	11	
2+	0	2	

Table 25.3 General evaluation and sports recovery status at 2-year follow-up

Parameters	Without NP ($n=72$)	With NP ($n=61$)	P value
Lysholm knee scale (average ± SD)	96 ± 5	94 ± 7	0.55
Patient satisfaction (percent) (average ± SD)	89 ± 10	89 ± 12	0.99
Sports performance recovery (percent) (average ± SD)	87 ± 13	88 ± 14	0.71
Tegner score (average; range)	6.7 (3–9)	6.6 (3–9)	0.59
Time to return to sports (month) (average ± SD)	8.7 ± 2.9	9.3 ± 3.6	0.46

Table 25.4 Subjective and objective findings with regard to knee extension

Follow-up period	Findings	Without NP ($n=72$)	With NP ($n=61$)	P value
6 months	Extension deficit (average ±)	0.8 ± 0.9	1.4 ± 1.3	0.012
	Subjective limited extension feeling			0.015
	Negative number (%)	57 (79)	57 (79)	
	1+	13 (18)	13 (18)	
	2+	2 (3)	2 (3)	
	Pain at passive full extension			0.39
	Negative number (%)	62 (86)	50 (82)	
	1+	6 (8)	9 (15)	
	2+	4 (6)	2 (3)	
1 year	Extension deficit	0.6 ± 0.8	1.1 ± 1.4	0.0054
	Subjective limited extension feeling			0.03
	Negative number (%)	65 (90)	47 (77)	
	1+	6 (8)	8 (13)	
	2+	1 (1)	6 (10)	
	Pain at passive full extension			0.57
	Negative number (%)	57 (79)	65 (90)	
	1+	13 (18)	6 (8)	
	2+	2 (3)	1 (1)	
2 year	Extension deficit	0.4 ± 0.7	0.9 ± 1.2	0.0053
	Subjective limited extension feeling			0.011
	Negative number (%)	70 (97)	52 (85)	
	1+	2 (3)	4 (7)	
	2+	1 (1)	5 (8)	
	Pain at passive full extension			0.83
	Negative number (%)	68 (94)	57 (93)	
	1+	3 (4)	4 (7)	
	2+	1 (1)	0 (0)	

patients requiring additional arthroscopic synovectomy for prolonged extension deficit (compared to no patients in the control group). The authors suggested that notchplasty site bleeding caused infrapatellar pad fibrosis and subsequent extension deficit. There were no differences between groups regarding muscle strength, patellofemoral findings, Lysholm or Tegner scores, Lachman or pivot-shift tests, graft failure, or return to sport. ATT as measured by KT-1000 was significantly less in the notchplasty group (0.4 versus 1.2 mm, $P=0.002$); however, this was attributed to knee over-constraint in the six notchplasty patients with extension deficit compared to only one in the control group. This study concluded that anatomic double-bundle ACL reconstruction without notchplasty allowed for physiologic graft–roof impingement without extension deficit. In a retrospective review of 75 patients, Muneta et al. [42] found no statistical differences in radiographic or clinical outcomes between notchplasty and non-notchplasty groups but reported that postoperative chronic synovitis occurred only in two patients in the non-notchplasty group. A recent case series found that smaller intercondylar notch dimensions were not a risk factor for graft failure following anatomic single- or double-bundle ACL reconstruction, and the authors did not endorse the use of notchplasty in conjunction with these reconstruction techniques [74].

25.4 A Paradigm Shift in ACL Reconstruction

In the 2000s, the technique of nonanatomic isometric ACL reconstruction utilizing notchplasty and posterior tibial tunnel placement was reconsidered due to an improved understanding of ACL anatomy and native ligament footprints [75]. "Anatomic" ACL reconstruction has been defined by van Eck et al. [76] as "the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites… to replicate normal anatomy, restore normal kinematics, and protect long-term knee health." Restoration of the anatomic ACL footprints was shown to result in more favorable knee kinematics and improved function [77–81]. However, with anatomic reconstruction, moving the tibial tunnel to a more anterior position raised concerns regarding notch impingement. Bedi et al. [82] used a cadaveric model to show that "over-the-top" and anterior tibial tunnel placements are better than posterior tunnel placement with respect to navigated Lachman and mechanized pivot-shift examinations; however, these positions increased the risk and magnitude of graft impingement with knee extension. The authors acknowledge that placing the tibial tunnel quite anteriorly may necessitate notchplasty and suggest that tunnel placement in the central aspect of the ACL footprint may confer the best balance between restoration of favorable knee kinematics and avoidance of graft impingement. Scheffel et al. [83] found that the tibial footprint does not vary according to intercondylar roof angle and concluded that it is a reliable landmark for tibial tunnel placement. Maak et al. [84] found that although graft impingement occurred with central, anteromedial, and posterolateral femoral tunnel positions, the risk and magnitude of impingement may be reduced by tunnel position in the center of the femoral ACL footprint. Issues and questions regarding tunnel placement are beyond the scope of this chapter; however, in contrast to the techniques advocated in the late twentieth century, these studies and many others showed that an anatomically placed ACL graft is not destined to impinge in the absence of notchplasty (Fig. 25.4).

A series of animal, cadaveric, and clinical studies by Iriuchishima and colleagues [85–89] has shown that impingement-free anatomic single-bundle and double-bundle ACL reconstruction is possible without notchplasty. In a porcine model, there were no significant differences in impingement pressures between nonanatomic and anatomic single-bundle reconstructions; however, there was a biomechanical advantage in ATT in the anatomic group [88]. In a cadaveric model, the authors evaluated impingement pressures for anatomic and nonanatomic tunnel positions on the tibia and femur [89]. Compared with the native ACL, there were no increased impingement pressures in either of the anatomic reconstruction groups. The authors acknowledge

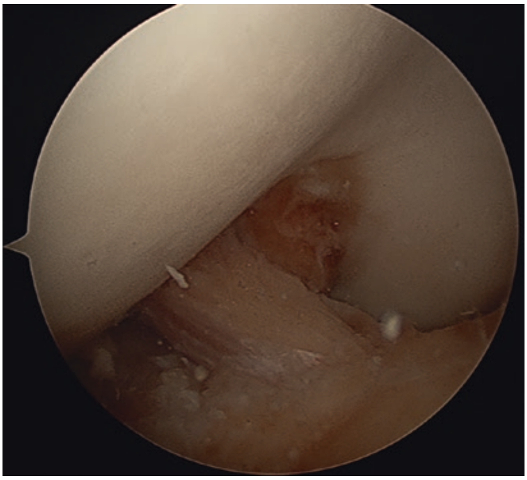

Fig. 25.4 Arthroscopic view of a right knee from the anterolateral portal showing the knee in full extension without intercondylar notch impingement of the ACL graft following primary reconstruction without notchplasty

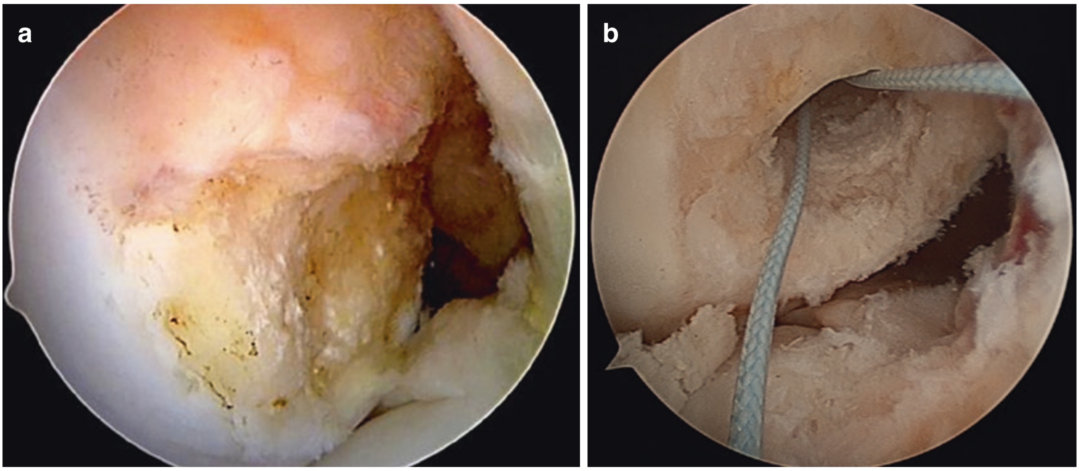

Fig. 25.5 Arthroscopic views of a right knee from the anteromedial portal showing clear visualization of the ACL femoral footprint, without prior notchplasty, before (**a**) and after (**b**) femoral tunnel drilling

that while natural contact may occur between the native ACL and the notch, the magnitude of this contact distinguishes it from pathologic impingement. Clinical studies using postoperative 3D-CT and MRI also showed that anatomic double-bundle ACL reconstruction could be performed without subsequent roof impingement [85, 87].

While some surgeons feel that notchplasty allows for a better view of the posterolateral margin of the intercondylar notch, others argue that the obliteration of osseous landmarks makes anatomic reconstruction and tunnel placement more difficult (Fig. 25.5) [46, 73, 76, 90, 91]. As part of their “footprint” technique, Bedi and Altchek [91] state that precise lateral portal placement 1–2 mm adjacent to the patellar tendon at the inferior patellar pole allows for visualization of the lateral wall of the notch and femoral ACL footprint without excessive notchplasty. Brown et al. [73] describe their “medial portal technique” in which the femoral ACL footprint is viewed from an anteromedial portal, eliminating the need for routine notchplasty for visualization. To achieve an unobstructed view of the lateral intercondylar notch, Cohen and Fu [92] describe using a central anteromedial viewing portal and an accessory anteromedial working portal for femoral tunnel drilling during double-bundle ACL reconstruction. However, in cases of revision surgery or chronic ACL deficiency in which the notch may be excessively stenotic due to bony hypertrophy or notch osteophyte formation, a modest and shallow notchplasty may be indicated to restore native notch geometry and adequately visualize the femoral footprint (Fig. 25.6) [73, 91, 93]. Even in cases of chronic ACL insufficiency in which the femoral footprint may be more difficult to identify, Shino et al. [94] were able to arthroscopically identify bony landmarks within the intercondylar notch that allowed for anatomic tunnel placement without the need for notchplasty.

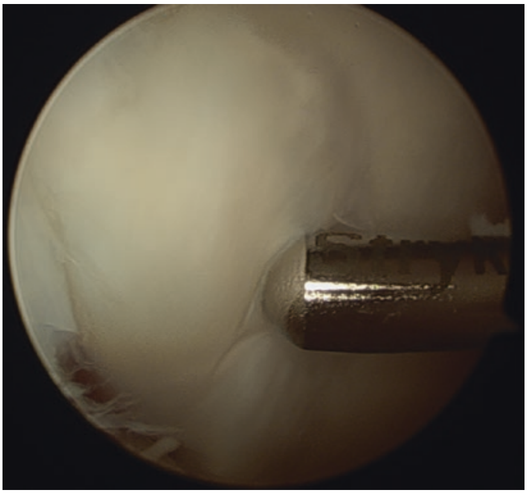

Fig. 25.6 Arthroscopic view of a left knee from the anteromedial portal during revision ACL reconstruction showing bony hypertrophy at the previous notchplasty site resulting in significant narrowing of the intercondylar notch

25.5 Author's Personal Experience and Indication for Notchplasty

Routine notch pasty is not recommended based on the results of our cohort study comparing with or without notchplasty (With-NP and Without-NP groups) in an anatomic double-bundle ACL reconstruction. Secondary arthroscopic procedures were necessary to improve extension limitation and pain induced by forced extension maneuver in six patients of the With-NP group and none of the Without-NP group. The second-look arthroscopy suggested that graft impingement could occur even if the correct anatomic ACL reconstruction was performed because the posterior tibial attachment of the normal ACL is narrow. Moreover, graft tissue runs straight between the tibial and femoral tunnels in the ACL reconstruction, which is different from the meticulous fiber arrangement of the normal ACL. The area of the ACL midsubstance is smaller than both tibial and femoral attachment areas, which also indicates the possibility of notch impingement in anatomic ACL reconstruction. In fact, from the findings of 42 second-look arthroscopies (24 cases of the Without-NP and 18 cases of the With-NP groups), tension and/or volume of the PL graft was insufficient in 10 cases of the Without-NP and in 1 of the With-NP groups. Selective performance of 2–3 mm wide notchplasty could be valuable to a patient with suspected poor healing and/or major instability and to a patient with graft–notch size mismatch after a usual anatomical graft placement.

25.6 Conclusions: Is Notchplasty Necessary for Anatomic ACL Reconstruction?

Preventing graft–notch impingement in ACL reconstruction is of paramount importance for avoiding postoperative graft abrasion and associated symptoms. Earlier strategies of posterior tibial tunnel placement and notchplasty have fallen out of favor given evidence that graft impingement can be avoided with anatomic ACL reconstruction without a notchplasty (Fig. 25.7). Notchplasty is antithetical to anatomic ACL reconstruction as it modifies native anatomy. Restoration of native ACL obliquity and footprint anatomy, though technically demanding, appears to be the most important factor for achieving favorable biomechanical and clinical outcomes. While surgeons must remain cognizant of the risk of graft impingement, utilizing meticulous anatomic reconstructive techniques appears to be sufficient to mitigate this risk. Nonanatomic tunnel position and notchplasty should not be used as the primary techniques for avoiding graft impingement.

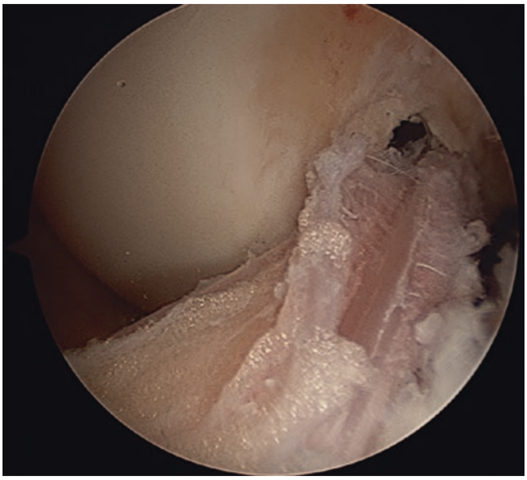

Fig. 25.7 Arthroscopic view of a right knee from the anteromedial portal showing primary ACL reconstruction and anatomic tunnel placement without notchplasty

References

1. Koga H, Muneta T, Yagishita K et al (2014) Effect of notchplasty in anatomic double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 42(8):1813–1821
2. Feagin JA Jr, Cabaud HE, Curl WW (1982) The anterior cruciate ligament: radiographic and clinical signs of successful and unsuccessful repairs. Clin Orthop Relat Res 164:54–58
3. Kieffer DA, Curnow RJ, Southwell RB, Tucker WF, Kendrick KK (1984) Anterior cruciate ligament arthroplasty. Am J Sports Med 12(4):301–312
4. Odensten M, Gillquist J (1985) Functional anatomy of the anterior cruciate ligament and a rationale for

reconstruction. J Bone Joint Surg Am 67(2): 257–262

5. Norwood LA Jr, Cross MJ (1977) The intercondylar shelf and the anterior cruciate ligament. Am J Sports Med 5(4):171–176
6. Goss BC, Hull ML, Howell SM (1997) Contact pressure and tension in anterior cruciate ligament grafts subjected to roof impingement during passive extension. J Orthop Res 15(2):263–268
7. Goss BC, Howell SM, Hull ML (1998) Quadriceps load aggravates and roofplasty mitigates active impingement of anterior cruciate ligament grafts against the intercondylar roof. J Orthop Res 16(5):611–617
8. Yaru NC, Daniel DM, Penner D (1992) The effect of tibial attachment site on graft impingement in an anterior cruciate ligament reconstruction. Am J Sports Med 20(2):217–220
9. Jagodzinski M, Leis A, Iselborn KW, Mall G, Nerlich M, Bosch U (2003) Impingement pressure and tension forces of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 11(2):85–90
10. Berns GS, Howell SM (1993) Roofplasty requirements in vitro for different tibial hole placements in anterior cruciate ligament reconstruction. Am J Sports Med 21(2):292–298
11. Fung DT, Zhang LQ (2003) Modeling of ACL impingement against the intercondylar notch. Clin Biomech (Bristol, Avon) 18(10):933–941
12. Howell SM, Taylor MA (1993) Failure of reconstruction of the anterior cruciate ligament due to impingement by the intercondylar roof. J Bone Joint Surg Am 75(7):1044–1055
13. Howell SM, Clark JA (1992) Tibial tunnel placement in anterior cruciate ligament reconstructions and graft impingement. Clin Orthop Relat Res 283:187–195
14. Howell SM, Clark JA, Farley TE (1991) A rationale for predicting anterior cruciate graft impingement by the intercondylar roof. A magnetic resonance imaging study. Am J Sports Med 19(3):276–282
15. Howell SM (1998) Principles for placing the tibial tunnel and avoiding roof impingement during reconstruction of a torn anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 6(Suppl 1):S49–S55
16. Good L, Odensten M, Gillquist J (1991) Intercondylar notch measurements with special reference to anterior cruciate ligament surgery. Clin Orthop Relat Res 263:185–189
17. Anderson AF, Lipscomb AB, Liudahl KJ, Addlestone RB (1987) Analysis of the intercondylar notch by computed tomography. Am J Sports Med 15(6):547–552
18. Souryal TO, Moore HA, Evans JP (1988) Bilaterality in anterior cruciate ligament injuries: associated intercondylar notch stenosis. Am J Sports Med 16(5):449–454
19. Houseworth SW, Mauro VJ, Mellon BA, Kieffer DA (1987) The intercondylar notch in acute tears of the anterior cruciate ligament: a computer graphics study. Am J Sports Med 15(3):221–224
20. Souryal TO, Freeman TR (1993) Intercondylar notch size and anterior cruciate ligament injuries in athletes. A prospective study. Am J Sports Med 21(4):535–539
21. Shelbourne KD, Davis TJ, Klootwyk TE (1998) The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. A prospective study. Am J Sports Med 26(3):402–408
22. LaPrade RF, Burnett QM 2nd (1994) Femoral intercondylar notch stenosis and correlation to anterior cruciate ligament injuries. A prospective study. Am J Sports Med 22(2):198–202; discussion 3
23. Keays SL, Keays R, Newcombe PA (2016) Femoral intercondylar notch width size: a comparison between siblings with and without anterior cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc 24(3):672–679
24. Simon RA, Everhart JS, Nagaraja HN, Chaudhari AM (2010) A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees. J Biomech 43(9):1702–1707
25. Hoteya K, Kato Y, Motojima S et al (2011) Association between intercondylar notch narrowing and bilateral anterior cruciate ligament injuries in athletes. Arch Orthop Trauma Surg 131(3):371–376
26. Swami VG, Mabee M, Hui C, Jaremko JL (2013) Three-dimensional intercondylar notch volumes in a skeletally immature pediatric population: a magnetic resonance imaging-based anatomic comparison of knees with torn and intact anterior cruciate ligaments. Arthroscopy 29(12):1954–1962
27. Whitney DC, Sturnick DR, Vacek PM et al (2014) Relationship between the risk of suffering a first-time noncontact ACL injury and geometry of the femoral notch and ACL: a prospective cohort study with a nested case-control analysis. Am J Sports Med 42(8):1796–1805
28. Zeng C, Gao SG, Wei J et al (2013) The influence of the intercondylar notch dimensions on injury of the anterior cruciate ligament: a meta-analysis. Knee Surg Sports Traumatol Arthrosc 21(4):804–815
29. Schickendantz MS, Weiker GG (1993) The predictive value of radiographs in the evaluation of unilateral and bilateral anterior cruciate ligament injuries. Am J Sports Med 21(1):110–113
30. Herzog RJ, Silliman JF, Hutton K, Rodkey WG, Steadman JR (1994) Measurements of the intercondylar notch by plain film radiography and magnetic resonance imaging. Am J Sports Med 22(2):204–210
31. Harner CD, Paulos LE, Greenwald AE, Rosenberg TD, Cooley VC (1994) Detailed analysis of patients with bilateral anterior cruciate ligament injuries. Am J Sports Med 22(1):37–43
32. Lombardo S, Sethi PM, Starkey C (2005) Intercondylar notch stenosis is not a risk factor for anterior cruciate ligament tears in professional male basketball players: an 11-year prospective study. Am J Sports Med 33(1):29–34

33. Teitz CC, Lind BK, Sacks BM (1997) Symmetry of the femoral notch width index. Am J Sports Med 25(5):687–690
34. Al-Saeed O, Brown M, Athyal R, Sheikh M (2013) Association of femoral intercondylar notch morphology, width index and the risk of anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 21(3):678–682
35. Ireland ML, Ballantyne BT, Little K, McClay IS (2001) A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 9(4):200–205
36. van Eck CF, Kopf S, van Dijk CN, Fu FH, Tashman S (2011) Comparison of 3-dimensional notch volume between subjects with and subjects without anterior cruciate ligament rupture. Arthroscopy 27(9):1235–1241
37. Sutton KM, Bullock JM (2013) Anterior cruciate ligament rupture: differences between males and females. J Am Acad Orthop Surg 21(1):41–50
38. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashiwaguchi S, Woo SL (1999) Quantitative analysis of human cruciate ligament insertions. Arthroscopy 15(7):741–749
39. Sturnick DR, Vacek PM, DeSarno MJ et al (2015) Combined anatomic factors predicting risk of anterior cruciate ligament injury for males and females. Am J Sports Med 43(4):839–847
40. Miller MD, Olszewski AD (1997) Posterior tibial tunnel placement to avoid anterior cruciate ligament graft impingement by the intercondylar roof. An in vitro and in vivo study. Am J Sports Med 25(6):818–822
41. Howell SM, Barad SJ (1995) Knee extension and its relationship to the slope of the intercondylar roof. Implications for positioning the tibial tunnel in anterior cruciate ligament reconstructions. Am J Sports Med 23(3):288–294
42. Muneta T, Yamamoto H, Ishibashi T, Asahina S, Murakami S, Furuya K (1995) The effects of tibial tunnel placement and roofplasty on reconstructed anterior cruciate ligament knees. Arthroscopy 11(1):57–62
43. Tanzer M, Lenczner E (1990) The relationship of intercondylar notch size and content to notchplasty requirement in anterior cruciate ligament surgery. Arthroscopy 6(2):89–93
44. Sapega AA, Moyer RA, Schneck C, Komalahiranya N (1990) Testing for isometry during reconstruction of the anterior cruciate ligament. Anatomical and biomechanical considerations. J Bone Joint Surg Am 72(2):259–267
45. Magill CD (1982) Arthroplastic reconstruction of anterior cruciate ligament: preliminary report of followup in 23 cases. Orthop Rev 11(4):59–64
46. Asahina S, Muneta T, Ezura Y (2000) Notchplasty in anterior cruciate ligament reconstruction: an experimental animal study. Arthroscopy 16(2):165–172
47. Berg EE (1991) Assessing arthroscopic notchplasty. Arthroscopy 7(3):275–277
48. Hame SL, Markolf KL, Hunter DM, Oakes DA, Zoric B (2003) Effects of notchplasty and femoral tunnel position on excursion patterns of an anterior cruciate ligament graft. Arthroscopy 19(4):340–345
49. Good L, Odensten M, Gillquist J (1987) Precision in reconstruction of the anterior cruciate ligament. A new positioning device compared with hand drilling. Acta Orthop Scand 58(6):658–661
50. Vergis A, Gillquist J (1995) Graft failure in intra-articular anterior cruciate ligament reconstructions: a review of the literature. Arthroscopy 11(3):312–321
51. Zuiderbaan HA, Khamaisy S, Nawabi DH et al (2014) Notchplasty in anterior cruciate ligament reconstruction in the setting of passive anterior tibial subluxation. Knee 21(6):1160–1165
52. Watanabe BM, Howell SM (1995) Arthroscopic findings associated with roof impingement of an anterior cruciate ligament graft. Am J Sports Med 23(5):616–625
53. Safran MR, Greene HS (2006) Avoidance and management of intra-articular complications of anterior cruciate ligament reconstruction. Instr Course Lect 55:475–488
54. Matava MJ, Muller MS, Clinton CM, Rodeo SA, Akhavan S, Parker RD (2009) Complications of anterior cruciate ligament reconstruction. Instr Course Lect 58:355–375
55. Kanamiya T, Hara M, Naito M (2002) Magnetic resonance imaging evaluation after re-notchplasty at second-look arthroscopy. Arthroscopy 18(6):584–588
56. Lane JG, Daniel DM, Stone ML (1994) Graft impingement after anterior cruciate ligament reconstruction. Presentation as an active extension "thunk". Am J Sports Med 22(3):415–417
57. Howell SM (1992) Arthroscopic roofplasty: a method for correcting an extension deficit caused by roof impingement of an anterior cruciate ligament graft. Arthroscopy 8(3):375–379
58. Fitch RB, Montgomery RD, Kincaid SA et al (1995) The effect of intercondylar notchplasty on the normal canine stifle. Vet Surg 24(2):156–164
59. LaPrade RF, Terry GC, Montgomery RD, Curd D, Simmons DJ (1998) The effects of aggressive notchplasty on the normal knee in dogs. Am J Sports Med 26(2):193–200
60. Mann TA, Black KP, Zanotti DJ, Barr M, Teater T (1999) The natural history of the intercondylar notch after notchplasty. Am J Sports Med 27(2):181–188
61. Ahn JH, Yoo JC, Yang HS, Kim JH, Wang JH (2007) Second-look arthroscopic findings of 208 patients after ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 15(3):242–248
62. Bents RT, Jones RC, May DA, Snearly WS (1998) Intercondylar notch encroachment following anterior cruciate ligament reconstruction: a prospective study. Am J Knee Surg 11(2):81–88
63. May DA, Snearly WN, Bents R, Jones R (1997) MR imaging findings in anterior cruciate ligament reconstruction: evaluation of notchplasty. AJR Am J Roentgenol 169(1):217–222

64. Morgan EA, McElroy JJ, DesJardins JD, Anderson DD, Steensen RN (1996) The effect of intercondylar notchplasty on the patellofemoral articulation. Am J Sports Med 24(6):843–846
65. Shino K, Nakagawa S, Inoue M, Horibe S, Yoneda M (1993) Deterioration of patellofemoral articular surfaces after anterior cruciate ligament reconstruction. Am J Sports Med 21(2):206–211
66. Pape D, Seil R, Adam F et al (2001) Blood loss in anterior cruciate ligament (ACL) reconstruction with and without intercondylar notchplasty: does it affect the clinical outcome? Arch Orthop Trauma Surg 121(10):574–577
67. Camillieri G, Margheritini F, Maresca G, Mariani PP (2001) Postoperative bleeding following notchplasty in anterior cruciate ligament reconstruction: thermal radio frequency versus powered instrumentation. Knee Surg Sports Traumatol Arthrosc 9(1): 12–14
68. Steiner ME, Murray MM, Rodeo SA (2008) Strategies to improve anterior cruciate ligament healing and graft placement. Am J Sports Med 36(1):176–189
69. Markolf KL, Hame SL, Hunter DM, Oakes D, Gause P (2002) Biomechanical effects of femoral notchplasty in anterior cruciate ligament reconstruction. Am J Sports Med 30(1):83–89
70. Keklikci K, Yapici C, Kim D, Linde-Rosen M, Smolinski P, Fu FH (2013) The effect of notchplasty in anterior cruciate ligament reconstruction: a biomechanical study in the porcine knee. Knee Surg Sports Traumatol Arthrosc 21(8):1915–1921
71. Seo YJ, Yoo YS, Kim YS et al (2014) The effect of notchplasty on tunnel widening in anterior cruciate ligament reconstruction. Arthroscopy 30(6):739–746
72. Fu FH, Bennett CH, Ma CB, Menetrey J, Lattermann C (2000) Current trends in anterior cruciate ligament reconstruction. Part II. Operative procedures and clinical correlations. Am J Sports Med 28(1):124–130
73. Brown CH, Spalding T, Robb C (2013) Medial portal technique for single-bundle anatomical Anterior Cruciate Ligament (ACL) reconstruction. Int Orthop (SICOT) 37(2):253–269
74. Wolf MR, Murawski CD, van Diek FM, van Eck CF, Huang Y, Fu FH (2015) Intercondylar notch dimensions and graft failure after single- and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 23(3):680–686
75. Schindler OS (2012) Surgery for anterior cruciate ligament deficiency: a historical perspective. Knee Surg Sports Traumatol Arthrosc 20(1):5–47
76. van Eck CF, Lesniak BP, Schreiber VM, Fu FH (2010) Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. Arthroscopy 26(2):258–268
77. Brophy RH, Voos JE, Shannon FJ et al (2008) Changes in the length of virtual anterior cruciate ligament fibers during stability testing: a comparison of conventional single-bundle reconstruction and native anterior cruciate ligament. Am J Sports Med 36(11):2196–2203
78. Cha PS, Brucker PU, West RV et al (2005) Arthroscopic double-bundle anterior cruciate ligament reconstruction: an anatomic approach. Arthroscopy 21(10):1275
79. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL (2003) Knee stability and graft function following anterior cruciate ligament reconstruction: Comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. Arthroscopy 19(3):297–304
80. Musahl V, Plakseychuk A, VanScyoc A et al (2005) Varying femoral tunnels between the anatomical footprint and isometric positions: effect on kinematics of the anterior cruciate ligament-reconstructed knee. Am J Sports Med 33(5):712–718
81. Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, Debski RE (2004) Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. Am J Sports Med 32(8):1825–1832
82. Bedi A, Maak T, Musahl V et al (2011) Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important? Am J Sports Med 39(2):366–373
83. Scheffel PT, Henninger HB, Burks RT (2013) Relationship of the intercondylar roof and the tibial footprint of the ACL: implications for ACL reconstruction. Am J Sports Med 41(2):396–401
84. Maak TG, Bedi A, Raphael BS et al (2011) Effect of femoral socket position on graft impingement after anterior cruciate ligament reconstruction. Am J Sports Med 39(5):1018–1023
85. Iriuchishima T, Horaguchi T, Kubomura T, Morimoto Y, Fu FH (2011) Evaluation of the intercondylar roof impingement after anatomical double-bundle anterior cruciate ligament reconstruction using 3D-CT. Knee Surg Sports Traumatol Arthrosc 19(4):674–679
86. Iriuchishima T, Shirakura K, Fu FH (2013) Graft impingement in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21(3):664–670
87. Iriuchishima T, Shirakura K, Horaguchi T, Morimoto Y, Fu FH (2011) Full knee extension magnetic resonance imaging for the evaluation of intercondylar roof impingement after anatomical double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19(Suppl 1):S22–S28
88. Iriuchishima T, Tajima G, Ingham SJ et al (2009) Intercondylar roof impingement pressure after anterior cruciate ligament reconstruction in a porcine model. Knee Surg Sports Traumatol Arthrosc 17(6):590–594
89. Iriuchishima T, Tajima G, Ingham SJ, Shen W, Smolinski P, Fu FH (2010) Impingement pressure in the anatomical and nonanatomical anterior cruciate ligament reconstruction: a cadaver study. Am J Sports Med 38(8):1611–1617
90. Karlsson J, Irrgang JJ, van Eck CF, Samuelsson K, Mejia HA, Fu FH (2011) Anatomic single- and

double-bundle anterior cruciate ligament reconstruction, part 2: clinical application of surgical technique. Am J Sports Med 39(9):2016–2026

91. Bedi A, Altchek DW (2009) The “Footprint” anterior cruciate ligament technique: an anatomic approach to anterior cruciate ligament reconstruction. Arthroscopy 25(10):1128–1138
92. Cohen SB, Fu FH (2007) Three-portal technique for anterior cruciate ligament reconstruction: use of a central medial portal. Arthroscopy 23(3):325 e1–325 e5
93. van Eck C, Working Z, Fu F (2011) Current concepts in anatomic single- and double-bundle anterior cruciate ligament reconstruction. Phys Sportsmed 39(2): 140–148
94. Shino K, Suzuki T, Iwahashi T et al (2010) The resident’s ridge as an arthroscopic landmark for anatomical femoral tunnel drilling in ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18(9): 1164–1168

Pros and Cons of Different ACL Graft Fixation Devices

26

Paul K. Herickhoff, Marc R. Safran, Patrick Yung, and Kai-Ming Chan

26.1 Introduction

The primary goal of graft fixation in ACL reconstruction (ACLR) is to provide strength and stiffness sufficient for rehabilitation and activities of daily living during the early postoperative period until biologic fixation has taken place in the bone tunnel. Many different devices have been designed to accommodate this goal. Although the mechanical properties of these devices is the focus of the majority of the published research on this topic, other important considerations include effects on graft healing within the tunnel, artifact on postoperative imaging, biologic reactions, need for hardware removal, and ease of revision ACL reconstruction. Although it is beyond the focus of this chapter and may vary in relation to market forces, cost is another important factor each surgeon should weigh when choosing a particular device.

The two predominant grafts used in ACL reconstruction are the bone-patellar tendon-bone (BPTB) and the semitendinosus and gracilis hamstring tendons (HT). These two grafts have different modes of healing – an important consideration when choosing a fixation device. The most common method of fixation of BPTB grafts is an interference screw in both the femoral and tibial tunnels. For HT grafts, a cortical button is most commonly used on the femoral side and an interference screw or other interference fixation is most commonly used on the tibial side. These well-established methods of fixation provide valuable benchmarks for biomechanical, clinical, and animal studies of new devices.

We begin our chapter with a brief review of the biomechanics and biology of ACL grafts and rehabilitation after ACL reconstruction, which will provide important context for the main focus of this chapter: the pros and cons of different ACL graft fixation devices.

26.2 Biomechanics

Biomechanical testing has shown that the BPTB and double-looped HT grafts show higher initial strength than the native ACL. The native ACL has an ultimate load to failure between 1,730 and 2,160 N [43, 67]. The corresponding values for a 10 mm BPTB graft and HT graft, by contrast, are 2,977 N [15] and over 4,000 N [22]. Therefore, the competence of the ACL graft construct immediately after surgery depends on the surgical fixation technique.

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The amount of force seen by the ACL graft after surgery is determined by the postoperative rehabilitation protocol. Escamilla and others recently reviewed cruciate ligament loading during common rehabilitation exercises. Early phase rehabilitation exercises including weight-bearing (WB), or closed kinetic chain, and non-weight-bearing (NWB), or open kinetic chain exercises, produce less than 4 % of peak ACL strain and peak ACL forces under 396 N. Level ground walking, which often is allowed immediately after surgery, places a peak anterior shear force of 355 N on the ACL. Explosive, plyometric exercises typically performed in later phases of ACL rehabilitation, such as single-leg landing and rapidly coming to a stop, on the other hand, produce ACL forces of approximately 1,300 N [17].

26.3 Biologic Healing of the ACL Graft

The ACL graft fixation is intended for immediate stability to allow early rehabilitation. The fixation device should provide an optimal healing environment for the graft to heal in the tunnels. Biodegradable devices must allow for an appropriate period of time to allow initial fixation and gradual degradation in order to enhance the eventual tunnel healing (Fig. 26.1). Animal studies have shown the fixation device is the weak link in ACL construct until 6 weeks after surgery for BPTB autografts [44] and 12 weeks after surgery for HT autografts [21, 51].

There are three distinct phases of graft healing in ACLR, including cell repopulation to the graft, proliferation phase, and remodeling phase. It is generally agreed that the graft undergoes necrosis and shows hypocellularity, especially in the center of the graft. Cytokines like TNF-α and interleukin 1-β are released as a consequence of necrosis, which then trigger growth factors for cell migration, proliferation, extracellular matrix (ECM) synthesis, and revascularization [36]. Maximum cellularity is observed during the proliferation phase and the cell number surpasses that of the intact ACL in numerous animal models [62]. Mesenchymal stem cells and activated fibroblasts can be found at the periphery of the graft in bone tunnel region and the mid-substance region [33]. Cell numbers regress toward the intact ACL cellularity at the end of the proliferation phase.

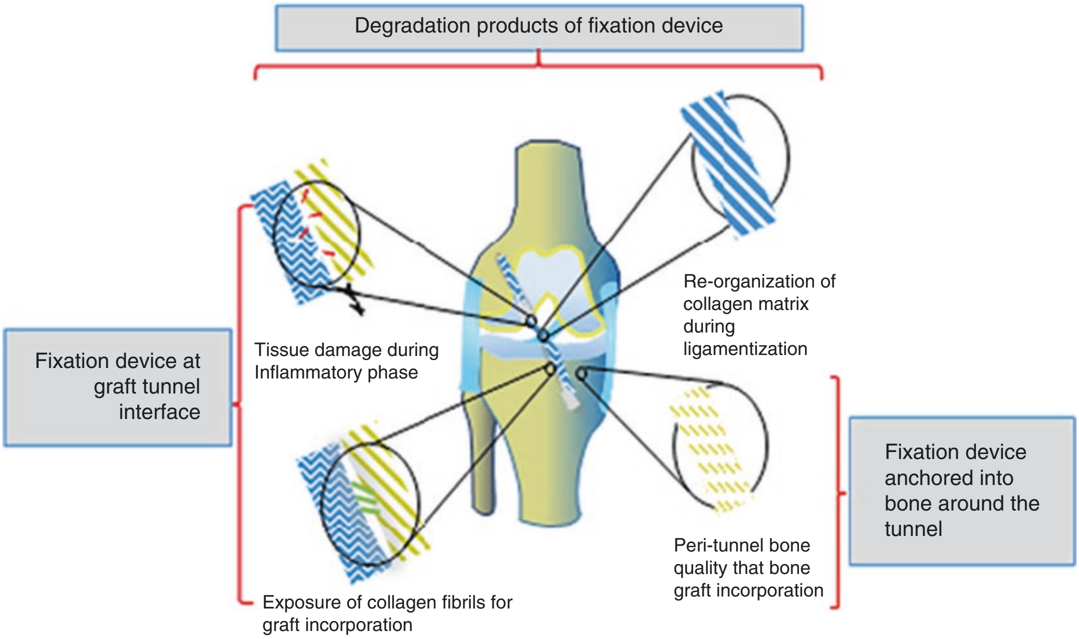

Fig. 26.1 Interactions of ACL fixation devices and graft healing

The tissue remodeling phase is started with cell-mediated restructuring of extracellular matrix as an adaptive response to mechanical loading on the tendon graft. Fixation devices inevitably affect these processes, and enhancement of graft healing could be achieved by introducing bioactive substances compatible to the surgical procedure. For examples, adding vitamin C into surgical irrigation saline can reduce graft necrosis and promote restoration in knee laxity in a rat model [19]. Intraoperative implantation of cells [37] or biomaterials [66] and postoperative injection of bioactive substances [20] can also promote graft healing in ACLR. These biological enhancements need to be compatible to the fixation device in use, and some bioactive substances could be engineered into the fixation device for a better outcome. Thus, fixation devices that enhance ACL biological healing may be the limelight of future development.

26.4 Femoral Versus Tibial Fixation

There are two key differences between femoral and tibial fixation. First, the bone mineral density of the proximal tibia is less than the distal femur. Bone mineral density has been shown to be directly related to interference screw fixation strength. Second, the line of force on the graft is directly in line with the tibial tunnel while it is obliquely oriented to the femoral tunnel in the weight-bearing position of extension [9]. For these reasons, the tibial graft fixation site is considered the weakest point in ACL reconstructions [1].

26.5 Pros and Cons of Different ACL Fixation Devices

ACL graft fixation devices can be broadly categorized as intratunnel, cortical button (“suspensory”), or extratunnel fixation depending on where the ACL graft is fixed (Fig. 26.1). In the next section, we will examine the issues related to the location of graft fixation, then review the merits and drawbacks of specific types of ACL graft fixation devices. A summary of the pros and cons of different graft fixation devices can be found in Table 26.1.

26.5.1 Graft Motion: Location of Graft Fixation

The motion of the ACL graft within a bone tunnel has been shown to be detrimental to graft healing [52] and may lead to tunnel widening [27]. Two types of graft-tunnel motion have been described, the “bungee effect” due to longitudinal graft motion and the “windshield wiper effect” due to transverse graft motion in the tunnel.

Rodeo and others used micro-CT to measure graft-tunnel motion in a rabbit model. They found graft-tunnel motion was greatest at the tunnel aperture and least at the tunnel exit. There was an inverse correlation between graft-tunnel motion and healing in the femoral tunnel [52]. Biomechanical studies have shown that aperture fixation reduces anteroposterior translation compared with suspensory fixation in BPTB grafts [29] and in HT grafts [61]. However, a study of HT and BPTB ACL reconstructions in cadavers found no significant difference in graft-tunnel motion between aperture and suspensory fixation [11].

Clinical studies have not shown an advantage of aperture fixation over suspensory fixation and no correlation between tunnel widening and functional outcome. A prospective study comparing HT and BPTB ACL reconstructions showed that despite increased tunnel widening in the HT cohort compared to the BPTB cohort, there was no significant difference in functional outcomes [14]. In a level 2 randomized controlled trial, Lubowitz and colleagues compared aperture fixation of the femoral and tibial tunnels with a cannulated retrograde screw to suspensory fixation with cortical buttons in all-inside allograft ACL reconstruction. At 2 years follow-up, there was no difference in knee stability, functional outcome scores or radiographic analysis for tunnel widening [38]. A meta-analysis of stability after ACL reconstruction as a function of fixation type

Table 26.1 Pros and cons of different ACL graft fixation devices

Fixation device	Metal interference screw (MIS)	Bioabsorbable interference screw	Screw and sheath	Cross-pins	Transfemoral suspensory pins	Cortical buttons	Spiked washer and screw	Screw and post	Staples
Pros	Excellent clinical track record	Equivalent clinical outcomes to MIS	Centralize the screw and increase graft to bone contact area in the tunnel	Simplify revision surgery	High load to failure	Excellent clinical track record	High load to failure	Reasonable load to failure, but less than other devices	Reasonable load to failure, but less than other devices
	Low complication rates	Simplify revision surgery	Higher radial forces than screw alone	Equivalent clinical outcomes with other devices	Equivalent clinical outcomes with other devices	Simplify revision surgery			
Cons	Artifact on MRI	Risk of screw breakage, postoperative knee effusion, and tunnel widening	Limited clinical studies	Breakage may occur	Breakage may occur	Adjustable loop devices may lengthen	Limited clinical studies	Limited clinical studies	Limited clinical studies
	Complicate revision surgery						May require complicated hardware removal	May require hardware removal	May require hardware removal

concluded that there is no stability advantage of aperture fixation compared with femoral suspensory fixation when using second-generation tibial fixation devices [50]. Based upon the currently available literature, the location of graft fixation has no correlation with clinical outcome (Figs. 26.2 and 26.3).

26.5.2 Interference Screws

Interference screws achieve aperture intratunnel fixation by stabilizing the graft close to the joint line. Interference screws have a long history of clinical success for both BPTB and HT autograft fixation [48]. One concern with interference

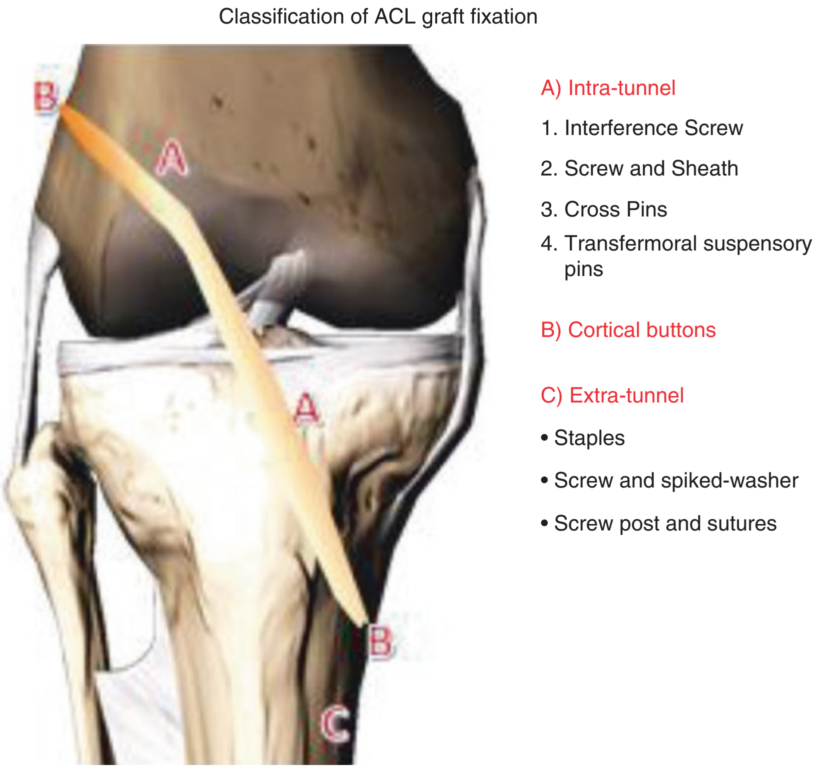

Fig. 26.2 Classification of ACL graft fixation by location

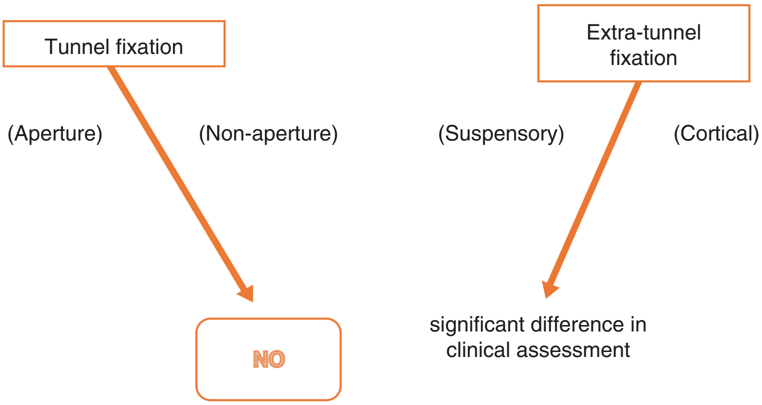

Fig. 26.3 Location of ACL graft fixation does not affect functional outcomes

screws for soft tissue grafts is that compressing the graft may affect its mechanical properties and biologic incorporation. In a sheep model of ACL reconstruction with autograft Achilles tendon fixed with biodegradable screws, the site of failure of all the grafts at 6 and 9 weeks postoperatively was the screw insertion site [65].

The ultimate load to failure of interference screws has been reported in several studies and ranges between 390 N [42] and 790 N [31]. However, many different parameters may influence fixation by interference screws, including the length and diameter of the screw, the position of the screw, its divergence, the size of the gap between the graft and tunnel diameter, the relative difference between tunnel size relative to screw size, corticocancellous versus cancellous fixation, and the torque of insertion of the screw.

26.5.2.1 Length of the Screw

The significance of the length of the screw in interference fixation is uncertain. In a study comparing the strength of endoscopically inserted interference screws for BPTB ACL reconstruction, there was no significant difference between 20 and 25 mm screw lengths [10]. Black and colleagues showed no significant differences in displacement, load to failure and stiffness between 12.5, 15, and 20 mm long interference screws of the same diameter for BPTB fixation in porcine tibias [8].

For soft tissue fixation, Harvey and colleagues showed a trend toward better fixation with longer metal interference screws [24]. Another study found similar results with bioabsorbable screws [64]. However, Stadelmaier and colleagues showed that there is no difference in strength between the screws of different lengths when the screw was advanced, so the tip of the screw was flush with the tibial plateau [58].

26.5.2.2 Diameter of the Screw

Increasing the diameter of the screw increases the fixation strength for both BPTB and HT ACL reconstruction. Kohn and Rose compared 7 and 9 mm metal interference screws in tibial and femoral tunnels for a 10 mm BPTB plug and showed superior fixation of the 9 mm screw on both sides [31]. The diameter of the screw may be more important for BPTB fixation strength when there is a larger gap between the bone block and tunnel wall. In a study of porcine tibias, no advantage was conferred by using a 9 mm screw compared with a 7 mm screw with gap sizes of 1–2 mm. When the gap was 3–4 mm, however, the 9 mm screw gave superior fixation [12].

For HT ACL reconstruction, Weiler et al. showed that tendons placed in tunnels of the same diameter and fixed by bioabsorbable screws of equal size had a lower strength of fixation than when fixed with screws oversized by 1 mm [64]. The downside to using an interference screw which is excessively large, however, is that it may lacerate the graft during screw insertion.

26.5.2.3 Position of the Screw

Central placement of an interference screw between the four limbs of a hamstring graft increases the area of bone-tendon contact available for healing in the tunnel [25]. A study of human cadaver knees conferred no advantage over eccentric placement, regarding load to failure and slippage at time zero, but did result in superior stiffness [54]. An experiment performed in a polyurethane foam model, however, showed no compromise in fixation with central compared with eccentric placement of the screw [55].

26.5.2.4 Divergence of the Screw

Angular deviation of the interference screw from the bone tunnel may occur during screw insertion, particularly on the femoral side. Divergent angles over 20° have been shown to reduce the strength of fixation in BPTB ACL reconstruction [25]. Screw divergence may be reduced by using a two-incision method using cannulated screws or by inserting the femoral screw through the same portal used to ream the femoral tunnel [25]. When using cannulated screws, the guidewire itself may diverge from the tunnel into the cancellous bone, a problem that may be corrected by using larger diameter guidewires. It is important to note, however, that no clinical studies have shown a correlation between screw divergence and laxity or clinical outcome [25].

26.5.2.5 Corticocancellous Versus Cancellous Fixation

Since cortical bone is stronger than cancellous bone, the pullout strength of the graft construct is increased by achieving corticocancellous fixation. In a study of calf bone, fixation with cancellous-only interference screw fixation demonstrated significantly lower load to failure and more slippage compared to corticocancellous fixation under cyclic loading [24].

26.5.2.6 Insertion Torque

The insertion torque of an interference screw has been shown to predict load to failure in both BPTB and HT grafts (Brown et al. 1996) [9]. For a given gap and screw size, the mean insertion torque for a metal screw is significantly higher than a bioabsorbable screw [45].

26.5.2.7 Bioabsorbable Versus Metal Interference Screws

Metal interference screws promote early integration into bone with high initial fixation strength and a higher load to failure than bioabsorbable screws in biomechanical studies [45]. Metal interference screws have afforded positive clinical outcomes and low complication rates and prevented excessive laxity. Drawbacks to using metal interference screws include complicated hardware removal during revision surgery and the creation of artifact on postoperative MRI [41].

Bioabsorbable interference screws, on the other hand, dissolve after 2–3 years, simplifying revision surgery, and do not cause artifact of postoperative MRI. However, complications have been reported with bioabsorbable screws, including breakage during surgery, bone tunnel widening, intra-articular screw migration, and foreign body reactions [41].

Several randomized controlled trials have been performed comparing metal and bioabsorbable interference screws. A recent systematic review of overlapping meta-analyses found similar clinical and functional outcomes between metal and bioabsorbable screws for BPTB and HT grafts. However, prolonged knee effusion, femoral tunnel widening, and screw breakage were more common with using bioabsorbable screws [41].

26.5.3 Screw and Sheath Devices

Combination screw and sheath devices have been designed for HT grafts to separate the grafts, secure concentric placement of the screw, and provide homogeneous friction between the tendon and the bone [1]. Biomechanical testing of these devices has shown varying results. A porcine study of six hamstring tendon graft fixation devices showed the screw and sheath device to have the highest load to failure (1,332 N) and lowest residual displacement [32]. In contrast, another biomechanical study of five different tibial fixation devices in a calf model showed the screw and sheath device to have the second lowest load to failure at 543 N [16]. In a bovine study, Smith and colleagues compared the radial force and pullout strength of two interference screws with two screw and sheath devices and found superior performance of screw and sheath devices for both measures [57]. Another biomechanical study in a porcine model comparing three interference screws and five screw and sheath devices showed no significant differences for ultimate failure load and cyclic displacement between the two fixation types, although the highest ultimate failure loads and least amount of cyclic displacement were observed for combination devices [1].

Clinical studies of screw and sheath devices are limited. One prospective clinical study comparing screw and sheath fixation, bioabsorbable interference screws, and cross-pins randomized into four groups showed no statistically or clinically relevant difference between the groups at 2 years of follow-up [23].

26.5.4 Cross-Pins

Cross-pin fixation achieves intratunnel fixation using biodegradable pins which pass through the substance of the graft. Cross-pins have been used for both BPTB and HT grafts on both the tibial and the femoral side and have the advantage of simplifying revision ACL reconstruction. Over 50 % of cross-pins may break; however, this has not been shown to affect clinical outcomes [3].

The load-to-failure of cross-pin fixation was 868 N and 994 N in two different biomechanical studies using porcine knees [31, 42]. Zantop and colleagues compared cross-pins with bioabsorbable interference screws in an ovine model of ACL reconstruction with an autograft Achilles tendon. At 6 weeks, the stiffness of the cross-pin group had improved by 52 % compared with the interference screw group, which decreased by 67 %. The strength of the interference screw constructs decreased by 81 % at 6 weeks, while the cross-screw group deteriorated only 48 % [68]. A biomechanical study of four different femoral soft tissue fixation devices in a porcine model, however, showed increased slippage of cross-pins and interference screws compared with cortical buttons and transfixation devices [2].

A small number of clinical studies have shown equivalent results using cross-pins compared to other ACL graft fixation devices. In a prospective, randomized trial of double-bundle ACL reconstruction with hamstring autograft, cross-pins were compared with cortical buttons. At a mean follow-up of 30 months, there was no statistically significant difference in subjective or objective outcomes, except for the KT-1,000 value, which was 1.30 mm in the cross-pin group versus 1.95 in the cortical button group [28]. Three studies have compared cross-pins with bioabsorbable interference screws and found no significant differences at 1, 2 and 5 years after surgery [18, 60, 63]. Bjorkman and colleagues showed no difference at 5 year follow-up between cross-pin fixation and metal interference screws in clinical or radiographic outcomes [7].

26.5.5 Transfemoral Suspensory Fixation Devices

Soft-tissue grafts may be fixed within the femoral tunnel by wrapping the grafts 180° around a metal or bioabsorbable transfixation pin. Bioabsorbable pins have the advantage over metal pins for revision ACL reconstruction; however, they also may break in 20 % of patients, can migrate out of the bone leading to iliotibial band irritation, and may cause femoral tunnel widening [13]. Complications have been reported during graft passage and fixation using this device [35].

Biomechanically, transfixation pins were found to have the highest load to failure (over 1,400 N) and greatest stiffness when compared with nine different femoral fixation devices tested [42]. Clinically, transfixation pins have shown 90 % satisfactory results at mid- to long-term follow-up [4]. Two prospective randomized studies comparing femoral transfixation pins with bioabsorbable interference screws and cortical buttons showed no difference in clinical outcomes at 1 and 2 years postoperatively [49, 53]. A recent registry study on revision rates of HT autograft ACL reconstructions performed in Norway from 2004 to 2013 showed that, among the devices used, the group with the lowest revision rate used a metal transfixation pin on the femur and metal interference screw on the tibia [46].

26.5.6 Cortical Buttons

Cortical buttons achieve suspensory fixation of HT and BPTB grafts on both the femoral and tibial sides. Although concerns have been raised that cortical buttons allow excessive movement of HT grafts in the tunnel leading to tunnel widening [27], one study which evaluated tunnel widening using four different fixation techniques showed the least amount of widening in the cortical button group [6].

Cortical buttons have shown excellent strength in biomechanical studies, with a load to failure of 1,086 N [31]. Several clinical studies have shown excellent stability and functional outcomes using cortical buttons [50]. Revision ACL reconstruction is simplified when cortical buttons were used in the primary surgery. Either a fixed-length or adjustable loop of fabric or braided, nonabsorbable suture fastens the graft to a metal button.

26.5.6.1 Fixed-Length Versus Adjustable Loop Cortical Buttons

Fixed-length cortical buttons present some technical challenges during surgery [5]. Because the loop length is predetermined, the surgeon must drill the tunnel to a specific depth then select a corresponding device of appropriate length. An error in measurement can lead to an inability to pass the button through the cortex or limit the length of the graft in the tunnel. Adjustable loop devices allow greater ease of insertion, allow complete fill of the femoral tunnel, obviate the need to calculate the loop length, and allow the same implant to be used regardless of tunnel placement or depth. Biomechanical testing has shown adjustable loop devices to have adequate load to failure testing (above 780 N); however, one concern is that cyclic loading results in lengthening of the loops, potentially leading to loosening of the graft or surgical failure [5, 30, 47].

26.5.7 Staples

Staples provide extra-tunnel fixation for HT grafts or BPTB grafts when there is a mismatch between the length of the graft and the tunnel. A biomechanical study comparing different methods of fixation of BPTB graft showed an inferior ultimate load to failure of staples compared with interference screw and screw-post fixation [34]. Another biomechanical study evaluated six tibial fixation methods using double-looped bovine tendon. Staples were found to have a load to failure of 705 N but 3.3 mm of slippage with 500 N load testing [39]. Staples may require later hardware removal for kneeling pain. A randomized controlled trial of HT ACL reconstruction in female patients compared metal interference screw fixation on the tibial side with metal interference screw plus supplementary staple fixation. At 2 years follow-up, the group with supplementary tibial fixation with staples had smaller side-to-side difference in KT-1,000 measurements but a higher incidence of kneeling pain [26].

26.5.8 Screw and Spiked Washer

Screw and spiked washer devices achieve extra-tunnel fixation of HT grafts by compressing the graft against the cortical bone on the tibia. Biomechanical testing of screw and spiked washers specially designed for ACL reconstruction has shown ultimate load to failure between 765 N and 945 N [31, 56]. In a sheep model, Singhatat and colleagues compared screw and spiked washer with bioabsorbable interference screw fixation of a digital extensor tendon transplanted into a bone tunnel. After 4 weeks of implantation, the strength and stiffness of the complex fixed with interference screws deteriorated 63 and 40 %, while the strength of the screw and spiked washer group at 4 weeks was similar to time zero and the stiffness improved 136 % [56]. Disadvantages of screw and spiked washer devices are the possible need to remove symptomatic hardware and may remove cortical bone attached to the device and a scarcity of clinical studies supporting their use.

26.5.9 Screw Post and Sutures

The free limbs of sutures attached to either HT or BPTB grafts may be secured by tying them around a screw, which is used as a post. Biomechanical testing of HT secured with suture and post showed a load to failure of 573 N [59]. A biomechanical study comparing different methods of fixation of BPTB grafts, however, showed an inferior ultimate load to failure of screw post fixation compared with interference screws [34]. Similar to screw and spiked washer devices, clinical studies of screw post and sutures are limited, and the prominent screw head may necessitate later hardware removal.

26.6 Summary

The primary goal of graft fixation in ACL reconstruction is to provide strength and stiffness sufficient for early rehabilitation and activities of daily living until biologic fixation has taken place in the bone tunnel. BPTB grafts require 6 weeks and HT grafts require 3 months of healing before adequate biologic fixation has taken place. Future improvements in fixation devices and techniques may improve the biologic healing of ACL grafts within the bone tunnel. No ACL graft fixation device is perfect. The surgeon must consider the advantages and disadvantages of the different ACL graft fixation devices before deciding which device to use for a particular patient.

References

1. Aga C, Rasmussen MT, Smith SD et al (2013) Biomechanical comparison of interference screws and combination screw and sheath devices for soft tissue anterior cruciate ligament reconstruction on the tibial side. Am J Sports Med 41(4):841–848
2. Ahmad CS, Gardner TR, Groh M et al (2004) Mechanical properties of soft tissue femoral fixation devices for anterior cruciate ligament reconstruction. Am J Sports Med 32(3):635–640
3. Ahn JH, Lee SA, Choi SH et al (2012) Femoral crosspin breakage and its effects on the results of anterior cruciate ligament reconstruction using a hamstring autograft. Arthroscopy 28(12):1826–1832
4. Asik M, Sen C, Tuncay I et al (2007) The mid- to long-term results of the anterior cruciate ligament reconstruction with hamstring tendons using transfix technique. Knee Surg Sports Traumatol Arthrosc 15(8):965–972
5. Barrow AE, Pilia M, Guda T et al (2014) Femoral suspension devices for anterior cruciate ligament reconstruction: do adjustable loops lengthen? Am J Sports Med 42:343–349
6. Bartlett RJ, Clatworthy MG, Nguyen TNV (2001) Graft selection in reconstruction of the anterior cruciate ligament. J Bone Joint Surg [Br] 83-B:625–634
7. Bjorkman P, Sandelin J, Harilainen A (2015) A randomized prospective controlled study with 5 year follow-up of cross-pin femoral fixation versus metal interference screw fixation in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthros 23(8):2353–2359
8. Black KP, Saunders MM, Stube KC et al (2000) Effects of interference fit screw length on tibial tunnel fixation for anterior cruciate ligament reconstruction. Am J Sports Med 28:846–849
9. Brand JC, Pienkowski D, Steenlage E et al (2000) Interference screw fixation strength of a quadrupled hamstring tendon graft is directly related to bone mineral density and insertion torque. Am J Sports Med 29(5):705–710
10. Brown CH Jr, Hecker AJ, Hipp JA et al (1993) The biomechanics of interference screw fixation of patellar tendon anterior cruciate ligament grafts. Am J Sports Med 21:880–886
11. Brown CH Jr, Wilson DR, Hecker AT et al (2004) Graft-bone motion and tensile properties of hamstring and patellar tendon anterior cruciate ligament femoral graft fixation under cyclic loading. Arthroscopy 20(9):922–935
12. Butler JC, Branch TP, Hutton WC (1994) Optimal graft fixation: the effect of gap size and screw size on bone plug fixation in ACL reconstruction. Arthroscopy 10:524–529
13. Choi NH, Son KM, Yoo SY et al (2012) Femoral tunnel widening after hamstring anterior cruciate ligament reconstruction with bioabsorbable transfix. Am J Sports Med 40(2):383–387
14. Clatworthy MG, Annear P, Bulow JU et al (1999) Tunnel widening in anterior cruciate ligament reconstruction: a prospective evaluation of hamstring and patellar tendon grafts. Knee Surg Sports Traumatol Arthrosc 7(3):138–145
15. Cooper DE (1998) Biomechanical properties of the central third patellar tendon graft: effect of rotation. Knee Surg Sports Traumatol Arthrosc 6(Suppl 1):S16–S19
16. Coleridge SD, Amis AA (2004) A comparison of five tibial-fixation systems in hamstring-graft anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 12:391–397
17. Escamilla RF, MacLeod TD, Wilk KE et al (2012) Cruciate ligament loading during common knee rehabilitation exercises. J Eng Med 226(9):670–680
18. Frosch S, Rittstieg A, Balcarek P et al (2012) Bioabsorbable interference screw versus bioabsorbable cross pins: influence of femoral graft fixation on the clinical outcome after ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 20:2251–2256
19. Fu SC, Cheng WH, Cheuk YC, Mok TY, Rolf C, Yung SH, Chan KM (2013) Development of vitamin C irrigation saline to promote graft healing in anterior cruciate ligament Reconstruction. J Ortho Trans 1(1):67–77
20. Fu SC, Cheuk YC, Chiu WY, Yung SH, Rolf CG, Chan KM (2015) Tripeptide-copper complex GHK-Cu (II) transiently improved healing outcome in a rat model of ACL reconstruction. J Orthop Res 33(7):1024–1033
21. Goradia VK, Rochat MC, Kida M et al (2000) Natural history of a hamstring tendon autograft used for anterior cruciate ligament reconstruction in a sheep model. Am J Sports Med 28(1):40–46
22. Hamner DL, Brown CH Jr, Steiner ME et al (1999) Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. J Bone Joint Surg 81-A:549–557
23. Harilainen A, Sandelin J (2009) A prospective comparison of 3 hamstring fixation devices; rigidfix, bioscrew and intrafix; randomized into 4 groups with 2 years of follow-up. Am J Sports Med 37(4):699–706

24. Harvey AR, Thomas NP, Amis AA (2003) The effect of screw length and position on fixation of four-stranded hamstring grafts for anterior cruciate ligament reconstruction. Knee 10:97–102
25. Harvey AR, Thomas NP, Amis AA (2005) Fixation of the graft in reconstruction of the anterior cruciate ligament. J Bone Joint Surg [Br] 87-B:593–603
26. Hill PF, Russell VJ, Salmon LJ et al (2005) The influence of supplementary tibial fixation on laxity measurements after anterior cruciate ligament reconstruction with hamstring tendons in female patients. Am J Sports Med 33(1):94–101
27. Hoher J, Moller HD, Fu FH (1998) Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? Knee Surg Sports Traumatol Arthrosc 7(4):215–219
28. Ibrahim SAR, Ghafar SA, Marwan Y et al (2014) Intratunnel versus extratunnel autologous hamstring double-bundle graft for anterior cruciate ligament reconstruction. A comparison of 2 femoral fixation procedures. Am J Sports Med 43(1):161–168
29. Ishibashi Y, Rudy TW, Livesay GA et al (1997) The effect of anterior cruciate ligament graft fixation site at the tibia on knee stability: evaluation using a robotic testing system. Arthroscopy 13:177–182
30. Johnson JS, Smith SD, Laprade CM et al (2014) A biomechanical comparison of femoral cortical suspension devices for soft tissue anterior cruciate ligament reconstruction under high loads. Am J Sports Med 43(1):154–160
31. Kohn D, Rose C (1994) Primary stability of interference screw fixation: Influence of screw diameter and insertion torque. Am J Sports Med 22(3):334–338
32. Kousa P, Jarvinen TLN, Vihavainen M et al (2003) The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction. Part II: tibial site. Am J Sports Med 31(2):182–188
33. Kuroda R, Kurosaka M, Yoshiya S, Mizuno K (2000) Localization of growth factors in the reconstructed anterior cruciate ligament: immunohistological study in dogs. Knee Surg Sports Traumatol Arthrosc 8:120–126
34. KurosakaM YS, Andrish JT (1987) A biomechanical comparison of different surgical techniques of graft fixation in anterior cruciate ligament reconstruction. Am J Sports Med 15:225–229
35. Lee YS, Ahn JH, Kim JG et al (2008) Analysis and prevention of intra-operative complication of TransFix fixation in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 16(7): 639–644
36. Lui PP, Lee YW, Mok TY, Cheuk YC, Chan KM (2013) Alendronate reduced peri-tunnel bone loss and enhanced tendon graft to bone tunnel healing in anterior cruciate ligament reconstruction. Eur Cell Mater 25:78–96
37. Lui PP, Wong OT, Lee YW (2014) Application of tendon-derived stem cell sheet for the promotion of graft healing in anterior cruciate ligament reconstruction. Am J Sports Med 42(3):681–689
38. Lubowitz JH, Schwartzberg R, Smith P (2015) Cortical suspensory button versus aperture interference screw fixation for knee anterior cruciate ligament soft-tissue allograft: a prospective, randomized controlled trial. Arthroscopy doi: 10.1016/j.arthro.2015.03.006
39. Magen HE, Howell SM, Hull ML (1999) Structural properties of six tibial fixation methods for anterior cruciate ligament soft tissue grafts. Am J Sports Med 27(1):35–43
40. Malhan K, Kumar A, Rees D (2002) Tibial cyst formation after anterior cruciate ligament reconstruction using a new bioabsorbable screw. Knee 9:73–75
41. Mascarenhas R, Saltzman BM, Sayegh ET et al (2015) Bioabsorbable versus metallic interference screws: a systematic review of overlapping meta-analysis. Arthroscopy 31(3):561–568
42. Milano G, Mulas PD, Ziranu N et al (2006) Comparison between different femoral fixation devices for ACL reconstruction with doubled hamstring tendon graft: a biomechanical analysis. Arthroscopy 22(6): 660–668
43. Noyes FR, Butler DL, Grood ES et al (1984) Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. J Bone Joint Surg 66A:344–352
44. Papageorgiou CD, Ma CB, Abramowitch SD et al (2001) A multidisciplinary study of the healing of an intraarticular anterior cruciate ligament graft in a goat model. Am J Sports Med 29(5):620–626
45. Pena F, Grontvedt T, Brown GA et al (1996) Comparison of failure strength between metallic and absorbable interference screws: influence of insertion torque, tunnel-bone block gap, bone mineral density and interference. Am J Sports Med 24:329–334
46. Persson A, Kjellsen AB, Fjeldsgaard K et al (2015) Registry data highlight increased revision rates for endobutton/biosure HA in ACL reconstruction with hamstring tendon autograft. A nationwide cohort study from the Norwegian knee ligament registry, 2004–2013. Am J Sports Med doi:10.1177/0363546515584757
47. Petre BM, Smith SD, Jansson KS et al (2012) Femoral cortical suspension devices for soft tissue anterior cruciate ligament reconstruction. A comparative biomechanical study. Am J Sports Med 41(2):416–422
48. Pinczewski LA, Lyman J, Salmon LJ et al (2007) A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: a controlled, prospective trial. Am J Sports Med 35:564–574
49. Price R, Stoney J, Brown G (2010) Prospective randomized comparison of endobutton versus cross-pin femoral fixation in hamstring anterior cruciate ligament reconstruction with 2-year follow-up. ANZ J Surg 80(3):162–165
50. Prodromos CC, Joyce BT, Shi K et al (2005) A meta-analysis of stability after anterior cruciate ligament reconstruction as a function of hamstring versus patellar tendon graft and fixation type. Arthroscopy 21(10):1202e1–1202e9

51. Rodeo SA, Arnoczky SP, Torzilli PA et al (1993) Tendon-healing in a bone tunnel. A biomechanical and histological study in the dog. J Bone Joint Surg 75-A:1795–1803
52. Rodeo SA, Kawamura S, Kim HJ et al (2006) Tendon healing in a bone tunnel differs at the tunnel entrance versus the tunnel exit: an effect of graft-tunnel motion? Am J Sports Med 34:1790–1800
53. Rose T, Hepp P, Venus J et al (2006) Prospective randomized clinical comparison of femoral transfixation versus bioscrew fixation in hamstring tendon ACL reconstruction: a preliminary report. Knee Surg Sports Traumatol Arthrosc 14(8):730–738
54. Shino K, Pflaster DS (2000) Comparison of eccentric and concentric screw placement for hamstring graft fixation in the tibial tunnel. Knee Surg Sports Traumatol Arthrosc 8:73–75
55. Simonian PT, Sussman PS, Baldini TH et al (1998) Interference screw position and hamstring graft location for anterior cruciate ligament reconstruction. Arthroscopy 14:459–464
56. Singhatat W, Lawhorn KW, Howell SM et al (2002) How four weeks of implantation affect the strength and stiffness of a tendon graft in a bone tunnel: a study of two fixation devices in an extraarticular model in ovine. Am J Sports Med 30(4):505–513
57. Smith KE, Garcia M, McAnuff K et al (2012) Anterior cruciate ligament fixation: is radial force a predictor of the pullout strength of soft-tissue interference screws? Knee 19:786–792
58. Stadelmaier DM, Lowe WR, Ilai OA et al (1999) Cyclic pull-out strength of hamstring tendon graft fixation with soft tissue interference screws. Influence of screw length. Am J Sports Med 27(6):778–783
59. Steiner ME, Hecker AT, Brown CH Jr et al (1994) Anterior cruciate ligament graft fixation: comparison of hamstring and patellar tendon grafts. Am J Sports Med 22:240–247
60. Stengel D, Casper D, Bauwens K et al (2009) Bioresorbable pins and interference screws for fixation of hamstring tendon grafts in anterior cruciate ligament reconstruction surgery. A randomized controlled trial. Am J Sports Med 37(9):1692–1698
61. Tsuda E, Fukuda Y, Loh JC et al (2002) The effect of soft-tissue graft fixation in anterior cruciate ligament reconstruction on graft-tunnel motion under anterior tibial loading. Arthroscopy 18(9):960–967
62. Unterhauser FN, Bail HJ, Hoher J, Haas NP, Weiler A (2003) Endoligamentous revascularization of an anterior cruciate ligament graft. Clin Orthop Relat Res 414:276–288
63. Volpi P, Marinoni L, Bait C et al (2009) Tibial fixation in anterior cruciate ligament reconstruction with bone-patellar tendon-bone and semitendinosus-gracilis autografts. A comparison between bioabsorbable screws and bioabsorbable cross-pin fixation. Am J Sports Med 37(4):808–812
64. Weiler A, Hoffmann RFG, Siepe CJ (2000) The influence of screw geometry on hamstring tendon interference fit fixation. Am J Sports Med 28(3): 356–359
65. Weiler A, Peine R, Pashmineh-Azar A et al (2002) Tendon healing in a bone tunnel. Part I: biomechanical results after biodegradable interference fit fixation in a model of anterior cruciate ligament reconstruction in sheep. Arthroscopy 18(2):113–123
66. Wen CY, Qin L, Lee KM, Chan KM (2009) The use of brushite calcium phosphate cement for enhancement of bone-tendon integration in an anterior cruciate ligament reconstruction rabbit model. Journal of biomedical materials research. Part B, App Biomaterials 89:466–474
67. Woo SL, Hollis JM, Adams DJ et al (1991) Tensile properties of the human femur-anterior cruciate ligament-tibia complex: the effects of specimen age and orientation. Am J Sports Med 19:217–225
68. Zantop T, Weimann A, Wolle K et al (2007) Initial and 6 weeks postoperative structural properties of soft tissue anterior cruciate ligament reconstructions with cross-pin or interference screw fixation: an in vivo study in sheep. Arthroscopy 23(1):14–20

ACL Graft Tensioning

27

Tatsuo Mae and Braden C. Fleming

27.1 Introduction

There are several variables under the control of the surgeon at the time of surgery that will influence the biomechanical behavior of the graft including graft type, graft position, graft tension, and the angle at which the tension is applied [2, 9–10, 17, 47, 48]. All of these variables will influence the loads in the graft post-surgery as well as the loads across the joint during activities of daily living. The initial tension at the time of graft fixation is one of the key factors for successful ACL reconstruction. While several studies have investigated the effect of initial graft tension on outcomes after ACL reconstruction, the optimal initial tension at graft fixation remains controversial. Excessively low initial graft tension may lead to a lax knee immediately after fixation, resulting in an unsatisfactory outcome and an increase in the risk of arthritis. Fleming et al. reported that anterior tibial displacement decreased during anterior tibial loading with an increase in initial graft tension in a cadaveric model of ACL reconstruction, and showed that higher initial graft tensions increased anterior knee stability [28]. Therefore, it could be reasonably assumed that it is important to apply a greater initial graft tension than what is required to set the physiological tension of the normal ACL for restoration of knee stability after ACL reconstruction to account for the stress relaxation, cyclic creep, and graft remodeling that occur after graft fixation. On the other hand, some investigators warn that excessive initial graft tension may lead to loss of extension, graft failure, and abnormal tibiofemoral positioning, also leading to cartilage degeneration [17, 25, 54, 55, 59, 76]. For example, Yoshiya et al. reconstructed the ACL in a canine model using a medial one-third patellar tendon autograft with initial graft tensions of 1 and 39 N [76]. Their results suggested that minimal graft tension should be applied, as poor vascularity and focal myxoid degeneration were found at 3 months when the grafts were tensioned to 39 N. When taken together, these studies suggest excessively low or high initial graft tension should be avoided. More studies are needed to determine the optimal initial graft tension at fixation during ACL reconstruction.

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27.2 Effect of Initial Graft Tension on Tibiofemoral Position Relationship

A properly positioned ACL graft courses from the supero-posterior margin of the lateral wall of the intercondylar notch to the anteromedial portion of the tibial plateau [23]. Due to the orientation of the ACL graft relative to the knee joint, an increase in initial graft tension applied to the distal end of the graft in the tibia will shift the tibia posteriorly, laterally, and proximally during the tensioning process of ACL reconstruction [4, 10, 25, 47] (Fig. 27.1). The proximal translation increases the tibiofemoral compressive forces in the medial and lateral compartments [10, 47], and it has been hypothesized that the posterior and lateral shift moves the tibiofemoral contact point to a location where the cartilage is thinner and less able to support the load [42, 65]. These findings suggest a potential mechanism to explain the onset and progression of posttraumatic osteoarthritis in the ACL-reconstructed knee [64]. An excessively large initial graft tension at the time of fixation may have a deleterious effect on the articular surface, leading to cartilage degeneration and/or a graft tear. An initial graft tension strategy that would restore the neutral tibiofemoral joint alignment could potentially lower the progression of posttraumatic osteoarthritis, yet such a system has not been introduced to date.

27.3 Viscoelastic Creep After Graft Fixation

Loss of tension during graft fixation [58, 75], the effects of cyclic loading [8, 13, 15, 36, 57, 61], and graft preconditioning [13, 26, 36, 61] are important factors that affect the outcome of ACL reconstruction surgery. Using a porcine cadaver model, Yoshihara et al. [75] showed that the residual loads following graft fixation were significantly different among fixation methods. They found that the maximum initial graft tension when applied manually by the surgeon resulted in mean graft tension values equal to 116, 54, and 25 N after interference screw, post, and button techniques, respectively. Whether the tension was objectively measured or applied by the surgeon, which have been shown to be equivalent [70], would not change these findings.

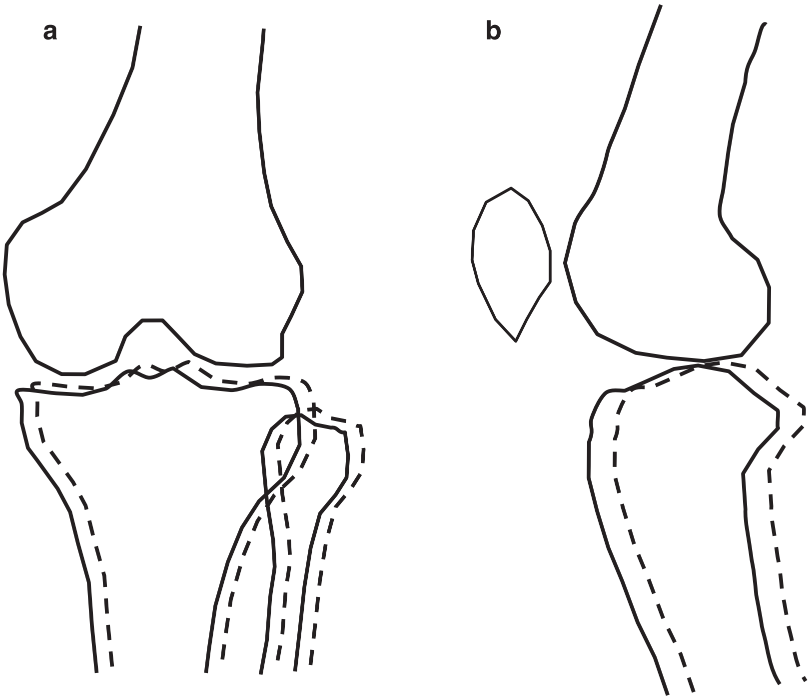

Fig. 27.1 Change of tibial position relative to femur with an increase in the initial graft tension. The initial position of the tibia without graft tension is illustrated by the *solid line*. When the graft is tensioned, tibia moves posteriorly, laterally, and proximally as indicated (by the *dashed line*). (**a**) Coronal plane and (**b**) sagittal plane

In a human cadaver study, an initial graft tension of 80 N was applied to soft tissue grafts fixed with interference screws with no preconditioning, cyclic preconditioning or isometric preconditioning applied to the graft prior to fixation [58]. A steady decrease of approximately 60 % occurred over 60 min. Likewise, Howard et al. measured the length change of bone-patellar tendon-bone graft during 4-min preconditioning and reported the graft length increased from 43.6 to 49.6 mm (a 14 % increase) [34].

Several investigators have shown that once the graft is fixed in the knee, anterior-posterior knee laxity increases with subsequent cycling. It has been reported that the tension in bone-patellar tendon-bone grafts dropped by 46 % at full extension after 1,500 cycles and that anterior-posterior knee laxity increased by 100 % after only 500 cycles [8]. This cyclic creep phenomenon is due in part to the viscoelastic behavior of ligament tissue [24], which appears to get worse in the days following ligament reconstruction, possibly due to enzymatic digestion [14]. Therefore, preconditioning the graft prior to implantation has been recommended to reduce stress relaxation and/or cyclic creep and to preserve graft tension following fixation.

27.4 Animal Studies

Translational animal models provide researchers the opportunity to evaluate graft healing in response to different treatment strategies including the effects of initial graft healing. The first landmark animal study of initial graft tension was performed by Yoshiya et al. [76]. Using the canine model, ACL reconstruction surgery was performed in both knees using the medial one-third of the patellar tendon as a graft. The graft in one knee was fixed under an initial graft tension of 1 N, while the other was fixed with an initial graft tension of 39 N. The investigators found that the high-tensioned grafts exhibited poor vascularity and focal degeneration.

In an effort to control the many different variables that could affect graft healing in an animal model, Katsuragi et al. then designed a bilateral canine model in which they first devitalized the ACLs via freezing and then cored out the tibial insertions [38]. In the right knee, an initial “graft” tension of 20 N was applied to the distal bone block while the bone block in the left knee was anatomically reduced. Significant reductions in the tensile strength and tangent modulus of the grafts were found in the grafts tensioned to 20 N after 12 weeks of healing. Histology revealed focal degeneration in the grafts tensioned to 20 N. These studies demonstrate that minimal tension should be applied to the graft materials during graft fixation in ACL reconstruction and that overtensioning may be deleterious to healing in this highly controlled setting.

Several subsequent animal studies of initial graft tension have been reported. Using initial graft tensions of 1 N, 7.5 N, and 17.5 N with patellar tendon grafts, it was shown that the high-tension grafts were superior both biomechanically and histologically to the low-tension grafts after 32 weeks of healing in the rabbit model [41]. To the contrary, a goat study comparing lax bone-patellar tendon-bone grafts to those tensioned to 44 N found that anterior-posterior knee laxity values between the two groups were not significantly different after 2 weeks of healing [19] and that the failure properties measured after 6 months were not significantly different [20]. These results were supported by another goat study in which patellar tendon grafts were tensioned to 5 N and 35 N [1]. While there were significant differences between the two initial graft tensions of 5 and 35 N at Time Zero, no significant differences in anterior-posterior knee laxity or graft failure properties were found after 6 weeks of healing. A recent rat study [31] comparing graft tensions of 2 N and 4 N also found no significant differences in the failure properties after 6 weeks of graft healing, though they presented qualitative histological evidence that the grafts of the high initial graft tension group was of higher integrity.

From the above review, the interpretations of the animal model results are conflicting with some studies showing that low tension is better and that high tension is superior,and the majority showing that there are no differences between high and low initial graft tensions. Unfortunately the use of animal models to evaluate the effects of initial graft tension is limited as a model for the human condition due to differences in joint anatomy, ranges of joint motion, and limb alignment [62] and because quadrupeds are more dependent on the ACL than humans [12]. Also, it is difficult to precisely control other surgical parameters, such as graft positioning, and post-operative rehabilitation, factors that will also affect graft integrity and outcomes. The novel model proposed by Katsuragi et al. was designed to eliminate some of these confounding variables [38], and their results clearly show that initial graft tension is an important factor to understand. While animal models provide insight into the effects of initial graft tension on graft healing, clinical studies are required to validate the findings of animal models and to ultimately determine which factors will ultimately affect clinical practice.

27.5 Clinical Studies

There are several clinical studies evaluating the effects of initial graft tension on clinical outcomes after ACL reconstruction. Yasuda et al. compared three different initial tensions at graft fixation (20, 40, and 80 N) with single-bundle ACL reconstruction using autogenous hamstring tendon graft in line with polyester tape. They reported that the postoperative side-to-side difference in anterior knee laxity was significantly less in the 80 N group compared to the 20 N group 2 years or more after surgery [73]. Thus they concluded that relatively high initial graft tensions reduced the postoperative anterior knee laxity after ACL reconstruction. Using patellar tendon autografts, Nicolas et al. reported significant differences in anterior-posterior knee laxity when initial graft tensions of 45 and 90 N were applied and that a graft tension of 45 N was not sufficient for restoring knee stability [56].

In contrast, Yoshiya et al. who reconstructed the ACL with patellar tendon autografts using two different initial tensions (25 and 50 N) [77] and Kim et al. who compared three initial tension levels (78, 117 and 147 N) with autogenous hamstring tendon grafts [39] reported no significant differences in clinical outcomes at final follow-up. Similarly, van Kampen et al. compared clinical outcomes 2 years after patellar tendon ACL reconstruction using initial graft tensions of 20 and 40 N, and they found no significant differences in outcomes between the two initial graft tension levels [71]. They also argued that the initial graft tension of 20 N seemed to be sufficient without the risk of over-constraining the knee joint. In an evidence-based review of the randomized control trials of initial graft tension, it was concluded that “there is no clear trend in terms of statistically significant or clinically relevant differences in terms of the amount of tension to apply to the graft during graft fixation” [5].

More recently, Mae and Shino previously performed 33 isometric Rosenberg bi-socket ACL reconstructions with hamstring tendon graft via three different amount of initial tension of 60, 80, and 100 N as a pilot study, and compared the side-to-side difference with KT Knee Arthrometer at 2-year follow-up among the three initial graft tension groups. The average side-to-side difference was 2.0 mm for 60 N, 1.1 mm for 80 N, and 1.6 mm for 100 N, respectively. While there were no significant differences between the initial tension conditions, they showed that the variation associated with the grafts tensioned to 100 N was the largest among three groups (Fig. 27.2). These results suggest that excessively high initial graft tensions may be unnecessary for improved ACL outcomes.

27.6 Laxity-Based Initial Graft Tension

Alternatively “laxity-based” initial graft tension protocols that restore or modulate anterior-posterior knee laxity at the time of surgery have also been recommended [3, 29, 30]. A “laxity-based” initial graft tension technique would provide benefits because it does not require the use of a tension measuring device, only an assessment of anterior-posterior knee laxity during the graft fixation procedure [29]. When using a laxity matching protocol, the initial graft tension can be

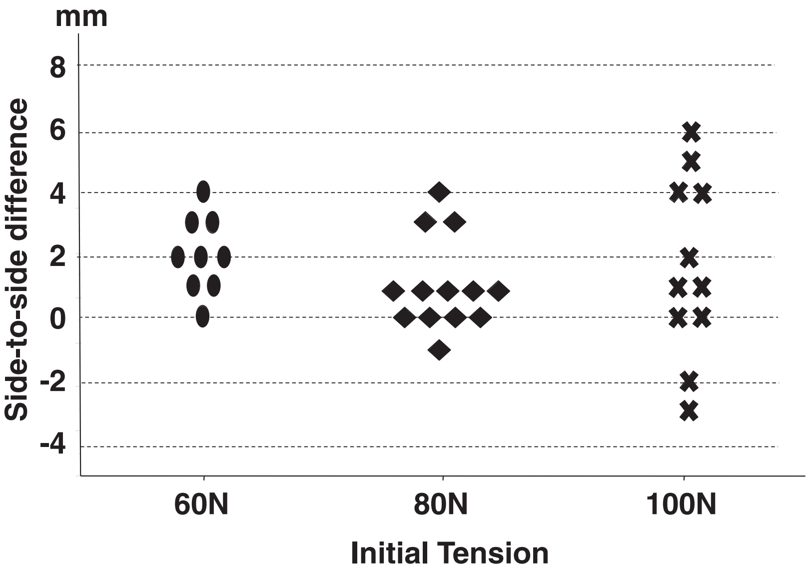

Fig. 27.2 Side-to-side difference using KT-1000 Knee Arthrometer 2 years after conventional ACL reconstruction with hamstring tendon graft via three different amounts of initial graft tension. The variation associated with the grafts tensioned to 100 N was the largest among three groups

adjusted to produce an anterior-posterior knee laxity value that is equal to or less than that of the contralateral normal knee [30], depending on the surgeon's preference. Laxity could either be objectively measured intraoperatively using an arthrometer [30] or subjectively using the Lachman and drawer test. In a cadaver study, it was determined that the laxity-based approach better restored normal knee laxity than the force-based approach at Time Zero [29]. However, in a recent prospective randomized clinical trial, it was determined that the setting the anterior-posterior knee laxity to be equal to that of the contralateral uninjured knee at the time of surgery resulted in equivalent outcomes when compared to over-constraining anterior-posterior knee laxity by 2 mm [30]. These data suggest that setting the anterior-posterior knee laxity within this laxity window at the time of surgery is a reasonable target.

27.7 Laxity-Matched Initial Graft Tension

The standard of tension required to determine the optimal initial tension is not known. However, a review of the literature suggests that a laxity-matched pretension (LMP), which is the graft tension required to obtain the normal anterior-posterior knee laxity in ACL reconstruction, may serve as a useful standard. One of the first cadaver studies evaluating the LMP was performed by Burks and Leland [16]. They measured the LMP for several graft materials in single-bundle ACL reconstruction and reported that the LMP value was 16 N for bone-patellar tendon-bone graft, 38 N for doubled semitendinosus graft, and 61 N for iliotibial band graft. They demonstrated that the required tension varied among graft materials. Other cadaver studies supported the general finding that graft type is a primary factor that must be accounted for when evaluating optimal initial graft tension strategies [2, 25, 37]. Surgical technique, including tunnel position and the number of tunnels, is also an important factor for determining the LMP in ACL reconstruction. The LMP value was 25 N for the conventional isometric Rosenberg technique with twin femoral tunnels and smaller than that using the same technique with a single femoral tunnel (44 N), while the LMP value for anatomic twin-tunnel technique (7.3 N) was smaller than that for the isometric Rosenberg twin femoral tunnel technique (25 N) [45, 46]. Therefore, the optimal graft initial tension should be determined, based on the graft materials and the operative techniques assuming no changes occur postoperatively.

27.8 Optimal Initial Graft Tension

27.8.1 Single-Bundle Reconstruction

The optimal initial graft tension should be slightly larger than the LMP to achieve good clinical outcomes, as the graft tension after fixation decreases because of stress relaxation or creep of the graft-fixation construct. Many cadaver studies have been performed to determine the optimal initial graft tension conditions that best restore normal knee joint laxity for single-bundle ACL reconstruction of various graft types [2, 4, 8–10, 15–17, 25, 28, 29, 32, 37, 44, 47, 48, 52, 57, 68, 70, 72, 78]. In summary, these studies report that initial graft tensions should be set anywhere between 0 and 60 N when performed between full extension and 30° flexion in an effort to best match the anterior-posterior laxity measurements of the ACL-intact knee.

27.8.2 Double-Bundle Reconstruction

A number of in vivo [21, 40, 74] and ex vivo [18, 33, 44, 63] Time Zero studies have also been performed to evaluate the initial graft tensions required to optimize double-bundle ACL reconstruction. These studies suggested that the tensions in each bundle were lower than that required for single-bundle ACL reconstruction. For anatomic double-bundle ACL reconstruction with hamstring tendon graft, Mae et al. reported 20 N of initial graft tension at 20° of knee flexion resulted in satisfactory clinical outcomes including KT side-to-side differences and second-look arthroscopic findings at 2 years postoperatively, while initial graft tensions less than 20 N were enough to provide satisfactory outcomes in a triple-bundle technique [49, 50, 67]. Markolf et al. measured the tension of the normal ACL in cadaveric knees, and these data serve as a bench mark for cadaver studies of initial graft tension. They reported that the ACL tension at 20° was nearly 0 N [51]. Thus if the initial graft tensioning is performed at 20°, a minimal initial graft tension level should be used to restore the tension pattern of the native ACL. An additional advantage of a lower initial graft tension magnitude is that less stress is imposed on the graft, its fixation sites, and the articular cartilage.

27.9 Effect of Graft Fixation

When fixing a hamstring tendon graft to the tibia, sutures are typically tied to a fixation post screw with manually applied “maximum” tension. However, the suture-post method includes some indefinite factors: (1) variability between surgeons, (2) risk of loosening or breakage of the sutures during knot tying, and (3) stress relaxation of the graft-suture fixation construct after fixation. Double staple techniques combined with polyester tape and spike washer with a screw for soft tissue grafts are also available to control tension with a tensioner [53]. However, these fixation techniques still run the risk of graft slippage, resulting in a loss of graft tension. With interference screw fixation, it is difficult to control the initial graft tension as the tension changes substantially during screw insertion. The double-spike plate (Meira Co., Nagoya, Japan) was developed for secure graft fixation with the intended tension (Fig. 27.3). Shino et al. reported that the graft tension after fixation with the double-spike plate temporarily increased while the base

Fig. 27.3 Radiographic view of graft fixation with the double-spike plate and screw at tibia

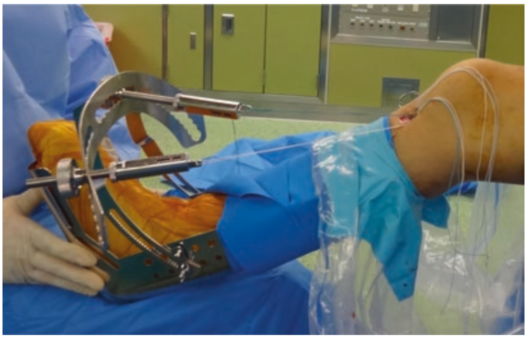

Fig. 27.4 Setting the initial graft tension using the metal shell boot (tensioning boot), which utilized two tensioners connected to the grafts via double-spike plates

spikes were hammered in place, but the intended tension was maintained even 5 min after fixation [66]. They showed the high reliability in initial fixation using the Double Spike Plate.

In the situation where the graft is tensioned with a tensioner, the tension is typically measured when the graft is manually pulled by the surgeon and is not adequately referenced to the tibia. While the manual technique is quite simple, the graft tension after fixation is likely to be variable because the position of the tibia relative to the femur is not controlled and because the tension measurement is referenced to the surgeon's hand which may not be transferred directly to the tibia. In this case, the tension in the graft when it is fixed may immediately decrease after fixation due to the subsequent posterior and proximal translation of tibia. A metal shell boot with tensioners connected to grafts (tensioning boot system; Meira Co., Nagoya, Japan) makes it possible to tension the grafts relative to the tibia, as the boot is fixed to the calf with a bandage (Fig. 27.4). It may be expected that the intended tension will remain in the graft after fixation using this tensioning boot system assuming no changes occur during the healing process.

27.10 Effect of Knee Flexion Angle

The initial graft tension does not change the shape of the graft tension versus flexion angle curve during passive flexion extension motion, but only shifts the entire curve up or down [17, 28, 52]. Given that the tension in the ACL graft after fixation is dependent on the knee flexion angle, it becomes clear that the knee flexion angle at which the tension is applied is extremely important. The tension in the ACL when the knee is at full extension is high, drops to a minimum or becomes slack at about 20–30°, and then increases with further flexion [11, 51]. If a graft is tensioned when the knee is at 30° of flexion, the entire tension-flexion curve is shifted upward increasing the tensions across the entire range of motion, particularly high at full extension. This effect of flexion angle on graft force in anatomic graft position can be larger than that in isometric graft position, as the graft length change in the former is larger than that in the latter [69]. In a cadaver study, Bylski-Austrow et al. demonstrated that an increase in knee flexion angle from 0 to 30° when the initial graft tension was applied increased the forces in the ligament across the entire range of motion [17]. As previously mentioned, an excessively large graft tension during range of motion may lead to abnormal tibiofemoral positioning, resulting in cartilage degeneration and a graft tear. This finding was verified by several other investigators [28, 60] and emphasized by Gertel [32]. Therefore, the knee flexion angle at which the initial graft tension is applied is an important parameter that must be designated and/or controlled when performing ACL reconstruction surgery.

27.11 Limitations of Biomechanical Studies

There are several limitations inherent to all Time Zero studies that must also be considered [27] when developing recommendations for optimal tension strategies for either single or double-bundle ACL reconstruction procedures. While cadaver experiments and Time Zero human experiments permit the use of tightly controlled experimental protocols and accurate data collection, the conclusions drawn may be limited in clinical relevance. While these studies provide important information of performance at the time of the ACL reconstruction, they do not take into account the changes that may occur during graft healing, such as tunnel enlargement [35, 43], viscoelastic changes [8, 13], graft remodeling [22], histologic degeneration and decreased vascularity [76], and the long-term consequences of cyclic creep even with graft preconditioning [13]. It is important to remember that the graft first undergoes a period of necrosis, followed by cell infiltration, revascularization, and then remodeling [6]. It is very likely that the initial graft tension condition at the time of surgery is not maintained. Translational and clinical studies that include the temporal effects of healing are paramount to determining the relevance of different initial graft tension strategies. While biomechanical and translational studies are important to understand the interactions between the initial parameters, only through carefully controlled, prospective randomized controlled trials will we better understand which initial graft tension parameters really matter.

27.12 Summary

Based on a review of the biomechanical, translational, and clinical studies on initial graft tension during ACL reconstruction surgery, the optimal initial graft tension strategies for different graft types remain unknown. It is clear from the animal studies that too much initial graft tension may be harmful to graft healing and promote cartilage degeneration, while too low of an initial graft tension must lead to the lax knee. However, the clinical studies, while varied, generally suggest that applying an initial graft tension slightly higher than the tension required to restore the normal anterior-posterior knee laxity may be optimal. In other words, the ideal initial graft tension might be set so that the laxity of reconstructed knee is within the window of 0–2 mm of over constraint.

We prefer to fix graft in anatomic ACL reconstruction with 10–20 N of initial tension using the tensioning boot, based on our previous studies of laxity-matched pretension [46, 49, 50]. Regarding the flexion angle at time of fixation, the graft when it is fixed in knee extension sometimes becomes slack in flexion because the knee angle of “extension” varies from individual to individual. Thus 20° of flexion is our preference, as the tension of normal ACL around 20° is minimal and has little variation.

References

1. Abramowitch SD, Papageorgiou CD, Withrow JD, Gilbert TW, Woo SL (2003) The effect of initial graft tension on the biomechanical properties of a healing ACL replacement graft: a study in goats. J Orthop Res 21(4):707–715
2. Amis AA (1989) Anterior cruciate ligament replacement: knee stability and the effects of implants. J Bone Joint Surg Br 71(5):819–824
3. Amis AA, Jakob RP (1998) Anterior cruciate ligament graft positioning, tensioning, and twisting. Knee Surg Sports Traumatol Arthrosc 6(Suppl 1):S2–S12
4. Andersen HN, Jorgensen U (1998) The immediate postoperative kinematic state after anterior cruciate ligament reconstruction with increasing perioperative tension. Knee Surg Sports Traumatol Arthrosc 6(Suppl 1):S62–S69
5. Arneja S, McConkey MO, Mulpuri K, Chin P, Gilbart MK, Regan WD, Jeith JM (2009) Graft tensioning in anterior cruciate ligament reconstruction: a systematic review of randomized controlled trials. Arthroscopy 25(2):200–207
6. Arnoczky SP, Tarvin GB, Marshall JL (1982) Anterior cruciate ligament replacement using patellar tendon. An evaluation of graft revascularization in the dog. J Bone Joint Surg Am 64(2):217–224
7. Arnold MP, Verdonschot N, van Kampen A (2005) The normal anterior cruciate ligament as a model for tensioning strategies in anterior cruciate ligament grafts. Am J Sports Med 33(2):277–283
8. Arnold MP, Lie DT, Verdonschot N, de Graaf R, Amis AA, van Kampen A (2005) The remains of anterior cruciate ligament graft tension after cyclic knee motion. Am J Sports Med 33(4):536–542
9. Austin JC, Phornphutkul C, Wojtys EM (2007) Loss of knee extension after anterior cruciate ligament reconstruction: effects of knee position and graft tensioning. J Bone Joint Surg Am 89(7):1565–1574
10. Brady MF, Bradley MP, Fleming BC, Fadale PD, Hulstyn MJ, Banerjee R (2007) Effects of initial graft tension on the tibiofemoral compressive forces and joint position following ACL reconstruction. Am J Sports Med 35(3):395–403
11. Beynnon BD, Fleming BC (1998) Anterior cruciate ligament strain in-vivo: a review of previous work. J Biomech 31(6):519–525
12. Boguszewski DV, Shearn JT, Wagner CT, Butler DL (2011) Investigating the effects of anterior tibial translation on anterior knee force in the porcine model: is the porcine knee ACL dependent? J Orthop Res 29(5):641–646

13. Boguszewski DV, Joshi NB, Wang D, Markolf KL, Petrigliano FA, McAllister DR (2015) Effect of different preconditioning protocols on anterior knee laxity after ACL reconstruction with four commonly used grafts. J Bone Joint Surg Am 97(13): 1059–1066
14. Boorman RS, Thornton GM, Shrive NG, Frank CB (2002) Ligament grafts become more susceptible to creep within days after surgery; evidence for early enzymatic degradation of a ligament graft in a rabbit model. Acta Orthop Scand 73(5):568–574
15. Boylan D, Greis PE, West JR, Bachus KN, Burks RT (2003) Effects of initial graft tension on knee stability after anterior cruciate ligament reconstruction using hamstring tendons: a cadaver study. Arthroscopy 19(7):700–705
16. Burks RT, Leland R (1988) Determination of graft tension before fixation in anterior cruciate ligament reconstruction. Arthroscopy 4(4):260–266
17. Bylski-Austrow DI, Grood ES, Hefzy MS, Holden P, Butler DL (1990) Anterior cruciate ligament replacements: a mechanical study of femoral attachment location, flexion angle at tensioning, and initial tension. J Orthop Res 8(4):522–531
18. Chen CH, Gadikota HR, Gill TJ, Li G (2011) The effect of graft fixation sequence on force distribution in double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19(5): 712–718
19. Cummings JF, Grood ES (2002) The progression of anterior translation after anterior cruciate ligament reconstruction in a caprine model. J Orthop Res 20(5):1003–1008
20. Cummings JF, Grood ES, Levy MS, Korvick DL, Wyatt R, Noyes FR (2002) The effects of graft width and graft laxity on the outcome of caprine anterior cruciate ligament reconstruction. J Orthop Res 20(2): 338–345
21. Cuomo P, Rama KR, Bull AM, Amis AA (2007) The effects of different tensioning strategies on knee laxity and graft tension after double-bundle anterior cruciate ligament reconstruction. Am J Sports Med 35(12): 2083–2090
22. Deehan DJ, Cawston TE (2005) The biology of integration of the anterior cruciate ligament. J Bone Joint Surg Br 87(7):889–895
23. Dodds JA, Arnoczky SP (1994) Anatomy of the anterior cruciate ligament: a blueprint for repair and reconstruction. Arthroscopy 10(2):132–139
24. Donahue TL, Gregersen C, Hull ML, Howell SM (2001) Comparison of viscoelastic, structural, and material properties of double-looped anterior cruciate ligament grafts made from bovine digital extensor and human hamstring tendons. J Biomech Engin 123(2):162–169
25. Eagar P, Hull ML, Howell SM (2004) How the fixation technique stiffness and initial tension affect anterior load-displacement of the knee and tension in anterior cruciate ligament grafts: a study in cadaveric knees using a double-loop hamstrings graft. J Orthop Res 22(3):613–624
26. Elias JJ, Kilambi S, Ciccone WJ 2nd (2009) Tension level during preconditioning influences hamstring tendon graft properties. Am J Sports Med 37(2): 334–338
27. Fleming BC (2014) Time zero. Am J Sports Med 42(7):1531–1533
28. Fleming BC, Beynnon BD, Howe JG, McLeod WD, Pope MH (1992) Effect of tension and placement of a prosthetic anterior cruciate ligament on the anteroposterior laxity of the knee. J Orthop Res 10(2):177–186
29. Fleming BC, Brady MF, Bradley MP, Banerjee R, Hulstyn MJ, Fadale PD (2008) Tibiofemoral compression force differences using laxity- and force-based initial graft tensioning techniques in the anterior cruciate ligament-reconstructed cadaveric knee. Arthroscopy 24(9):1052–1060
30. Fleming BC, Fadale PD, Hulstyn MJ, Shalvoy RM, Oksendahl HL, Badger GJ, Tung GA (2013) The effect of initial graft tension after anterior cruciate ligament reconstruction: a randomized clinical trial with 36-month follow-up. Am J Sports Med 41(1):25–34
31. Fu SC, Cheng WH, Cheuk YC, Mok TY, Rolf CG, Yung SH, Chan KM (2013) Effect of graft tensioning on mechanical restoration in a rat model of anterior cruciate ligament reconstruction using free tendon graft. Knee Surg Sports Traumatol Arthrosc 21(5): 1226–1233
32. Gertel TH, Lew WD, Lewis JL, Stewart NJ, Hunter RE (1993) Effect of anterior cruciate ligament graft tensioning direction, magnitude, and flexion angle on knee biomechanics. Am J Sports Med 21(4):572–581
33. Hoshino Y, Kuroda R, Nagamune K, Nishimoto K, Yagi M, Mizuno K, Yoshiya S, Kurosaka M (2007) The effect of graft tensioning in anatomic 2-bundle ACL reconstruction on knee joint kinematics. Knee Surg Sports Traumatol Arthrosc 15(5):508–514
34. Howard ME, Cawley PW, Losse GM, Johnston RB 3rd (1996) Bone-patellar tendon-bone grafts for anterior cruciate ligament reconstruction: the effects of graft pretensioning. Arthroscopy 12(3):287–292
35. Jagodzinski M, Foerstemann T, Mall G, Krettek C, Bosch U, Paessler HH (2005) Analysis if forces of ACL reconstructions at the tunnel entrance: is tunnel enlargement a biomechanical problem. J Biomech 38(1):23–31
36. Jisa KA, Williams BT, Jaglowski JR, Turnbull TL, LaPrade RF, Wijdicks CA (2015) Lack of consensus regarding pretensioning and preconditioning protocols for soft tissue graft reconstruction of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc (in press) 2015 Feb 26. [Epub ahead of print]
37. Karchin A, Hull ML, Howell SM (2004) Initial tension and anterior load-displacement behavior of high-stiffness anterior cruciate ligament graft constructs. J Bone Joint Surg Am 86(8):1675–1683
38. Katsuragi R, Yasuda K, Tsujino J, Keira M, Kaneda K (2000) The effect of nonphysiologically high initial tension on the mechanical properties of in situ frozen anterior cruciate ligament in a canine model. Am J Sports Med 28(1):47–56

39. Kim SG, Kurosawa H, Sakuraba K, Ikeda H, Takazawa S (2006) The effect of initial graft tension on posteoperative clinical outcome in anterior cruciate ligament reconstruction with semiteninosus tendon. Arch Orthop Trauma Surg 126(4):260–264
40. Koga H, Muneta T, Yagishita K, Watanabe T, Mochizuki T, Horie M, Nakamura T, Otabe K, Sekiya I (2015) Effect of initial graft tension on knee stability and graft tension pattern in double-bundle anterior cruciate ligament reconstruction. Arthroscopy. doi:10.1016/j.arthro.2015.03.012
41. Labs K, Perka C, Scheneider F (2002) The biological and biomechanical effect of different graft tensioning in anterior cruciate ligament reconstruction: an experimental study. Arch Orthop Trauma Surg 122(4): 193–199
42. Li G, Moses JM, Papannagari R, Pathare NP, Defrate LE, Gill TJ (2006) Anterior cruciate ligament deficiency alters the in vivo motion of the tibiofemoral cartilage contact points in both the anteroposterior and mediolateral directions. J Bone Joint Surg Am 88(8):1826–1834
43. L'Insalata JC, Klatt B, Fu FH, Harner CD (1997) Tunnel expansion following anterior cruciate ligament reconstruction: a comparison of hamstrings and patellar tendon grafts. Knee Surg Sports Traumatol Arthrosc 5(4):234–238
44. Luites JW, Wymenga AB, Blankevoort L, Kooloos JM, Verdonschot N (2012) Computer-assisted anatomically placed double-bundle ACL reconstruction: an in vitro experiment with different tension angles for the AM and the PL graft. Med Eng Phys 34(8): 1031–1036
45. Mae T, Shino K, Miyama T, Shinjo H, Ochi T, Yoshikawa H, Fujie H (2001) Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: biomechanics analysis using a robotic simulator. Arthroscopy 17(7):708–716
46. Mae T, Shino K, Matsumoto N, Hamada M, Yoneda M, Nakata K (2007) Anatomical two-bundle versus Rosenberg's isometric bi-socket ACL reconstruction: a biomechanical comparison in laxity match pretension. Knee Surg Sports Traumatol Arthrosc 15(4):328–334
47. Mae T, Shino K, Nakata K, Toritsuka Y, Otsubo H, Fujie H (2008) Optimization of graft fixation at the time of anterior cruciate ligament reconstruction. Part I: effect of initial tension. Am J Sports Med 36(6): 1087–1093
48. Mae T, Shino K, Nakata K, Toritsuka Y, Otsubo H, Fujie H (2008) Optimization of graft fixation at the time of anterior cruciate ligament reconstruction. Part II: effect of knee flexion angle. Am J Sports Med 36(6):1094–1100
49. Mae T, Shino K, Matsumoto N, Natsu-ume T, Yoneda K, Yoshikawa H, Yoneda M (2010) Anatomic double-bundle anterior cruciate ligament reconstruction using hamstring tendons with minimally-required initial tension. Arthroscopy 26(10):1289–1295
50. Mae T, Shino K, Matsumoto N, Yoneda K, Yoshikawa H, Nakata K (2013) Immediately postoperative anterior knee stability: double- versus triple-bundle anterior cruciate ligament reconstructions. Arthroscopy 29(2):213–219
51. Markolf KL, Gorek JF, Kabo M, Shapiro MS (1990) Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. J Bone Joint Surg Am 72(4):557–567
52. Markolf KL, Hame S, Hunter DM, Oakes DA, Zoric B, Gause G, Finerman GA (2002) Effects of femoral tunnel placement on knee laxity and forces in an anterior cruciate ligament graft. J Orthop Res 20(5):1016–1024
53. Magen HE, Howell SM, Hull ML (1999) Structural properties of six tibial fixation methods for anterior cruciate ligament soft tissue grafts. Am J Sports Med 27(1):35–43
54. Melby A III, Noble JS, Askew MJ, Boom AA, Hurst FW (1991) The effects of graft tensioning on the laxity and kinematics of the anterior cruciate ligament reconstructed knee. Arthroscopy 7(3):257–266
55. Nabors ED, Richmond JC, Vannah WM, McConville OR (1995) Anterior cruciate ligament graft tensioning in full extension. Am J Sports Med 23(4):488–492
56. Nicolas SJ, D'Amato MJ, Mullaney MJ, Tyler TF, Kolstad K, McHugh MP (2004) A prospectively randomized double-bundle study on the effect of initial graft tension on knee stability afer anterior cruciate ligament reconstruction. Am J Sports Med 32(8):1881–1886
57. Numazaki H, Tohyama H, Nakano H, Kikuchi S, Yasuda K (2002) The effect of initial graft tension in anterior cruciate ligament reconstruction on the mechanical behaviors of the femur-graft-tibia complex during cyclic loading. Am J Sports Med 30(6): 800–805
58. Nurmi JT, Kannus P, Sievanen H, Jarvela T, Jarvinen M, Jarvinen TL (2004) Interference screw fixation of soft tissue grafts in anterior cruciate ligament reconstruction: part 2: effect of preconditioning on graft tension during and after screw insertion. Am J Sports Med 32(2):418–424
59. O'Donoghue DH, Rockwood CCA Jr, Frank GR, Jack SC, Kenyon R (1966) Repair of the anterior cruciate ligament in dogs. J Bone Joint Surg Am 48(3):503–519
60. Pena E, Martinez MA, Calvo B, Palanca D, Doblare M (2005) A finite element simulation of the effect of graft stiffness and graft tensioning in ACL reconstruction. Clin Biomech (Bristol, Avon) 20(6):636–644
61. Pilia M, Murray M, Guda T, Heckman M, Appleford M (2015) Pretensioning of soft tissue grafts in anterior cruciate ligament reconstruction. Orthopedics 38(7):e582–e587
62. Proffen BL, McElfresh M, Fleming BC, Murray MM (2012) A comparative anatomical study of the human knee and six animal species. Knee 19(4):493–499
63. Sasaki Y, Chang SS, Fujii M, Araki D, Zhu J, Marshall B, Linde-Rosen M, Smolinski P, Fu FH (2015) Effect of fixation angle and graft tension in double-bundle anterior cruciate ligament reconstruction on knee biomechanics. Knee Surg Sports Traumatol Arthrosc 16:28

64. Scanlan SF, Lai J, Donahue JP, Andriacchi TP (2012) Variations in the three-dimensional location and orientation of the ACL in healthy subjects relative to patients after transtibial ACL reconstruction. J Orthop Res 30(6):910–918
65. Scanlan SF, Favre J, Andriacchi TP (2013) The relationship between peak knee extension at heel-strike of walking and the location of thickest femoral cartilage in ACL reconstructed and healthy contralateral knees. J Biomech 46(5):849–854
66. Shino K, Mae T, Maeda A, Miyama T, Shinjo H, Kawakami H (2002) Graft fixation with predetermined tension using a new device, the double spike plate. Arthroscopy 18(8):908–911
67. Shino K, Nakata K, Nakamura N, Mae T, Otsubo H, Iwahashi T, Nakagawa S (2005) Anatomic anterior cruciate ligament reconstruction using two double-looped hamstring tendon grafts via twin femoral and triple tibial tunnels. Oper Tech Orthop Surg 15: 130–134
68. Simmons R, Howell SM, Hull ML (2003) Effect of the angle of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on tension of an anterior cruciate ligament graft: an in vitro study. J Bone Joint Surg Am 85(6):1018–1029
69. Take Y, Mae T, Nakata K, Nakagawa S, Tachibana Y, Shino K (2015) Excursion of bone-patellar tendon-bone grafts during the flexion-extension movement in anterior cruciate ligament reconstruction. Comparison between isometric and anatomic reconstruction techniques. Asia Pacific J Sports Med Arthosc Rehabil Technol 2(3):85–89
70. Thompson DM, Hull ML, Howell SM (2006) Does a tensioning device pinned to the tibia improve knee anterior-posterior load-displacement compared to manual tensioning of the graft following anterior cruciate ligament reconstruction? A cadaveric study of two tibial fixation devices. J Orthop Res 24(9):1832–1841
71. van Kampen A, Wymenga AB, van der Heide HJ, Bakens HJ (1998) The effect of different graft tensioning in anterior cruciate ligament reconstruction: a prospective randomized study. Arthroscopy 14(8):845–850
72. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30(5):660–666
73. Yasuda K, Tsujino J, Tanabe Y, Kaneda K (1997) Effects of initial graft tension on clinical outcome after anterior cruciate ligament reconstruction. Autogenous doubled hamstring tendons connected in series with polyester tapes. Am J Sports Med 25(1):99–106
74. Yasuda K, Ichiyama H, Kondo E, Miyatake S, Inoue M, Tanabe Y (2008) An in vivo biomechanical study on the tension-versus-knee flexion angle curves of 2 grafts in anatomic double-bundle anterior cruciate ligament reconstruction: effects of initial tension and internal tibial rotation. Arthroscopy 24(3):276–284
75. Yoshihara Y, Yoshiya S, Kurosaka M, Yamamoto T, Kuroada R, Muratsu H (2005) The load of an implanted graft during and after fixation in anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 13(2):101–106
76. Yoshiya S, Andrish JT, Manley MT, Bauer TW (1987) Graft tension in anterior cruciate ligament reconstruction. An in vivo study in dogs. Am J Sports Med 15(5):464–470
77. Yoshiya S, Kurosaka M, Ouchi K, Kuroda R, Mizuno K (2002) Graft tension and knee stability after anterior cruciate ligament reconstruction. Clin Orthop Relat Res 394:154–160
78. Zavras TD, Race A, Amis AA (2005) The effect of femoral attachment location on anterior cruciate ligament reconstruction: graft tension patterns and restoration of normal anterior-posterior laxity patterns. Knee Surg Sports Traumatol Arthroscopy 13(2):92–100

Diagnosis of Partial ACL Rupture

28

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28.1 Clinical Examination

Proper clinical examination is very important in the early identification of partial ACL tears. Two main clinical tests help the surgeon to determine if the patient has a complete or partial ACL rupture.

The clinical exam must be evaluated in the setting of the MRI, laximetry, and radiographic findings. It is a compilation of all of the information which will lead to a precise diagnosis of a partial tear functional or not functional and then help in the final surgical decision.

28.1.1 The Lachman Test

The traditional Lachman test in 20–30° of knee flexion provides valuable information regarding the integrity of the ACL. Three major points must be emphasized for the evaluation of this test: (a) the amount of anterior tibial translation is calculated and is considered abnormal when it is over 10 mm. In cases of partial ACL tears, this translation can be less and may not be observed by an inexperienced surgeon. A firm, repetitive, and cautious application of the Lachman test is advised. (b) The presence of a firm endpoint is crucial to be noted. A solid ACL prevents tibia from excessive anterior translation but also results in an abrupt endpoint, which may also be felt by the patient. A complete tear will result in excessive anterior translation that also ends more smoothly, while a partial tear will also lack of this abrupt feeling of a stop. (c) Very important is also to perform the Lachman test on the contralateral knee. The comparison of the injured with the healthy knee provides very useful information about the pre-injury status of the ACL and the patient's native anterior tibial translation, the latter of which is variable among individuals. In the case of an injured or previously operated contralateral knee, this test has reduced value, and caution is advised in the interpretation of the results.

It is very important to note that both clinical tests, Lachman and pivot-shift, may have falsely negative results in the case where a concomitant

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bucket-handle meniscus injury prevents excessive anterior or rotatory tibial translation. Imaging findings of such injury (MRI) help the surgeon to be aware of these cases.

The use of Lachman test with stress x-rays and rolimeter for the diagnosis of partial versus complete ACL tears has been recently published by Panisset et al. (a comparison of Telos™ stress radiography versus Rolimeter™ in the diagnosis of different patterns of anterior cruciate ligament tears), where the authors showed that partial ACL tears have positive Lachman test and side-to-side difference of anterior tibial translation of less than 5 mm, in comparison to complete ACL tears where grossly positive Lachman test was recorded, with no firm endpoint and difference greater than 5 mm.

28.1.2 The Pivot-Shift Test

The pivot-shift test (PST) is pathognomonic for ACL tear. When positive, it demonstrates that the ACL is nonfunctional [1]. The PST seems to be the most reliable testing maneuver in the identification of posterolateral bundle tears according to Petersen and Zantop [2]. This is supported by other authors who recorded increased positive PST results in cases of posterolateral bundle ruptures, while the anterior drawer test and the Lachman test may remain negative [3]. On the contrary, there is limited data that the less frequent anteromedial bundle tears result in greater laxity in Lachman test and minor laxity or even negative results in PST [4]. But Petersen indicated that a clinical study validating the PST and the LT in cases of isolated PL and AM bundle ruptures has not been performed [2].

More recently, Dejour et al. performed a study comparing PST results in complete versus different types of partial ACL tears [5]. They showed that laxity in the PST (+2 and +3) was the most consistent clinical finding in identifying complete ACL tears (86.4 %) vs. partial tears (23.6 %, $p < 0.0001$), yet it was not useful to distinguish between the different types of partial ACL tear (30.3 % in PL-intact and 19 % in AM-intact tears, p: NS). Lachman test was of similar diagnostic value and it recorded severe laxity (+2) in 99 % of complete tears vs. 32.6 % ($p < 0.001$) in all types of partial ACL tears. The different subgroups of partial ACL tears showed 2+ Lachman laxity in 33.3 % of AM tears vs. 25.7 % of PL tears ($p < 0.01$ when compared to LT +1).

28.2 MRI

The use of MRI in the diagnosis of partial ACL tears has been focused on finding specific imaging patterns according to the type of rupture [6]. In a recent study by Van Dyck et al., the authors did a retrospective study in the MRI images of 51 patients with arthroscopic confirmation of partial ACL tear. They concluded that MRI has a low level of accuracy in the identification of such injuries, mainly because of the significant overlap of the imaging findings between partial tears and complete tears and mucoid degeneration of ACL and the presence of the initial posttraumatic hematoma [7]. Whenever a partial ACL tear was diagnosed, identification of which bundle was torn was not possible. In a recent study by Dejour, 300 cases of partial and complete ACL tears where included [5]. MRI findings showed significant overlap among the different injury types; they were mostly classified as the "absence or severe distortion of ACL fibers" for all types of ACL tears, with nonsignificant difference between complete (96 %) and all types of partial tears combined (73 %, p: NS). In the cases of partial tears, it was generally not possible to locate tears in the AM or PL bundle of the ligament, and there was no correlation between the preoperative MRI findings and the arthroscopic type of ACL tear. The only significant pattern was recorded between the diagnoses of "absence or severe distortion of ACL fibers" with complete ACL tears (96 %, $p < 0.0001$).

28.3 Instrumented Laxity

The preoperative diagnosis or the suspicion of partial ACL tear based on the preoperative clinical tests, laxity measurements, and MRI findings is important because even under arthroscopy, it is not always easy to decide whether the remaining bundle represents a partial ACL rupture or a partial synovial healing after complete ACL rupture. In addition, as stated by Dejour et al. [5], the preoperative diagnosis or the suspicion of partial ACL tear could affect the type of treatment (conservative or surgical), the steps of the surgery (choice of graft, diagnostic arthroscopy before graft harvesting), and the surgical technique (standard ACL reconstruction or ACL augmentation). In standard single- or double-bundle ACL reconstruction, the ACL remnant is generally completely debrided in order to enable clear visualization for making the bone tunnels. However, several surgeons reported advantages of ACL augmentation (remnant-preserving ACL reconstruction) from the point of view of knee stability, proprioception of the knee, MRI findings, bone tunnel widening, or better synovial coverage of the graft [8–16].

Objective quantification of anterior tibial translation is a decisional aid for surgeons in identifying a partial or complete ACL tear because clinical examination is examiner dependent. Quantitative measurement of knee laxity after ACL injury has been performed clinically with several types of laximetry devices.

28.3.1 Laximetry Device

Several arthrometers are available for measurement of anterior tibial translation. The KT-1000™ (MEDmetric®, San Diego, California, USA), developed by Daniel et al. [17, 18], is the first and the most widely used knee ligament testing system because it is an easy-to-use device and has been a reference instrument in the many published scientific papers. The KT-1000 has allowed orthopedic surgeons to document the extent of knee injury by measuring in mm of the degree of side-to-side differences between normal and injured knees. The KT-2000 uses the same components as the KT-1000 with added feature of graphic documentation. The Rolimeter™ (Aircast, Summit, USA) is as reliable as the KT-1000™ and simple. The radiological Telos™ stress device (Metax, Hungen, Germany) is widely used in Europe. The GNRB® system (Genourob, Laval, France) has been recently developed in an attempt to improve intra- and inter-examiner reproducibility. The Kneelax (Monitored Rehab Systems, Netherlands) is similar in size and shape to the KT-1000 but updates the recording procedure by the use of user-friendly computerized software. Reproducibility of the laximetry devices depends on the examiner's experience, the type of laximetry device, the ability of the patient to relax, and the quality of patient's positioning.

Using 300 consecutive ACL-deficient patients with isolated ACL tears, Dejour et al. tested the hypothesis that complete and partial ACL tears demonstrate different patterns in clinical testing combined with instrumented laxity tests [5]. All patients were tested clinically with the Lachman test and the pivot-shift test. In addition, preoperative objective evaluation included bilateral stress radiography with the Telos™ stress device using 15 kg. In their study, instrumented laxity results showed a significant difference in side-to-side difference of anterior tibial translation in complete tears (9.1 ± 3.4 mm) versus partial tears (5.2 ± 2.9 mm). Partial ACL tears with functional remaining fibers had pivot-shift grades of 0 or +1 and less than a 4 mm side-to-side difference in stress radiographs.

Lefevre et al. [19] and Robert et al. [20] used GNRB® arthrometer to evaluate the partial ACL injury. Lefevre et al. compared the results of the GNRB® arthrometer to those of Telos™ in the diagnosis of partial ACL injury in 139 patients [19]. ACL surgery was performed in 109 patients, 97 ACL reconstruction for complete ACL injury and 12 single-bundle ACL augmentation for partial ACL injury. Conservative treatment was indicated in 30 patients with partial ACL injury. Conservative treatment was proposed for cases of partial ACL tear without pain or instability according to the patient, an ACL which appeared to have healed on MRI, and laxity of less than 5 mm with the Telos™ device and/or less than 3 mm with GNRB®. They showed that the side-to-side anterior instrumented laxity of full and partial thickness tears were significantly different with the two tests. The differential laxity threshold for partial ACL tear with GNRB® at 250 N was 2.5 mm with a sensitivity of 84 % and a specificity of 81 % and with the Telos™ device at 250 N was 3.6 mm with a sensitivity of 81.5 % and a specificity of 59.5 %.

Nakamae and Ochi et al. investigated the relationship between morphological pattern of ACL remnant and anterior knee laxity using the KT-2000 arthrometer [21]. In their study, instrumented laxity results showed a significant difference in side-to-side difference of anterior tibial translation in complete tears (6.5 mm) versus partial tears (3.2 mm). They concluded that partial rupture of the ACL should be suspected when the side-to-side difference in the anterior displacement of the tibia was less than 5 mm and a delayed firm endpoint was noted. They also described that the decision of whether the remaining bundle represents partial rupture or complete rupture of the ACL was made on the basis of physical, MRI, and arthroscopic findings in a comprehensive manner.

Sonnery-Cottet et al. showed that preoperative side-to-side anterior instrumented laxity was less than 6 mm in all patients in partial ACL rupture group compared with 60 % in complete ACL rupture group [22]. The preoperative differential instrumented laxity was measured in all patients with the Rolimeter arthrometer. On average, preoperative side-to-side difference of knee laxity was 7.5 mm in complete ACL rupture group and 4.8 mm in partial ACL rupture group. They concluded that partial rupture of the ACL should be suspected when the differential instrumented laxity is equal to or less than 6 mm with a typical delayed firm anterior endpoint during the Lachman test.

In summary, several clinical reports on preoperative evaluation of ACL injury have shown the different instrumented laxity measurements between arthroscopically confirmed complete and partial ACL tears. Objective quantification of anterior tibial translation is a decisional aid for surgeons in identifying a partial or complete ACL tear. The knees with complete ACL tear seem to have higher anterior tibial translation and also have greater laxity with the Lachman and pivot-shift tests when compared with the knees with partial ACL tears. When preoperative side-to-side difference of anterior knee laxity is relatively small (less than 3–6 mm), arthroscopy may demonstrate a thick and abundant ACL remnant, maintaining a bridge between the tibia and the intercondylar notch.

28.3.2 Navigation System

A computer navigation system for ACL reconstruction is not used only to improve the accuracy of the ACL reconstruction procedure but also to enable researchers to collect objective and quantitative data of biomechanical function of the knee. Intraoperative arthrometry with a navigation system before and immediately after resection of the ACL remnant in cases of partial ACL rupture is an ideal approach to evaluate the biomechanical function of the ACL remnant. This procedure can directly measure the function of the preserved bundle after ACL injury. With a navigation system, Nakamae and Ochi et al. evaluated the biomechanical function of ACL remnants in anteroposterior and rotational knee stability in patients with ACL injury [21]. In the study, they found that ACL remnants contributed to anteroposterior knee stability evaluated at 30° knee flexion for up to 1 year after injury, beyond which this biomechanical function was lost. The authors also found that ACL remnant had no contribution to rotational knee stability at any stage after injury. However, they evaluated biomechanical function of the ACL remnant only in patients with a complete ACL rupture (the femoral attachment of the ACL remnant was positioned abnormally). They could not evaluate the function of the ACL remnant in patients with a partial ACL rupture because in such cases, they performed an ACL augmentation procedure that preserves the remnant. Another limitation of the study was that they did not compare the stability of injured and uninjured knees, because the use of 2.4 mm K-wires to fasten transmitters to the femur and tibia of the uninjured leg was deemed to be overly invasive.

Maeda et al. also evaluated the biomechanical function of ACL remnants using a navigation system [23]. They concluded that although ACL remnants bridging the lateral wall of the intercondylar notch to the tibia significantly decreased anterior knee laxity in knee extension, the knee stability provided by the ACL remnants was not adequate. However, in their study, there was no category of partial ACL tear in their classification. Nakase et al. also evaluated knee laxity in anterior tibial translation and rotation following removal of ACL remnants using a computer navigation system [24]. They reported that ACL remnants contributed to anteroposterior and rotatory knee laxity evaluated at 30° knee flexion and concluded that their type 3 remnant (remnant bridging between the anatomical insertions of the ACL on the lateral wall of the femoral condyle and the tibia) should be preserved as much as possible when ACL reconstruction surgery is performed. Although there was no category of partial ACL tear in their classification, they described that the patients with a partial tear of the ACL may have been included in type 3 and may have influenced the results.

28.3.3 Electromagnetic Measurement System

Arthrometers have been used in order to evaluate almost mainly anteroposterior translation and not dynamic rotation as is seen in the pivot-shift test. Although the computer navigation system can evaluate anterior knee laxity and tibial rotation, it cannot be utilized in the outpatient clinic because K-wires must be inserted into the tibia and femur in order to fasten transmitters to the bones. Based on the background, noninvasive measurement systems have been developed. Recently, a three-dimensional electromagnetic measurement system (EMS) has been used to quantitatively evaluate knee laxity during the Lachman test and the pivot-shift test [25–27].

Araki et al. investigated the biomechanical function of ACL remnants in ACL-deficient knees with both partial and complete tears using an EMS [28]. They evaluated 20 knees of partial ACL injury, 20 knees of complete ACL injury, and 40 intact knees. In order to measure the biomechanical function of the knee, the side-to-side difference of anteroposterior tibial translation during the Lachman test and the acceleration during the pivot-shift test were calculated using the EMS. According to quantitative assessment using the EMS, mean side-to-side differences during the Lachman test were 3.1 ± 2.1 mm in the partial ACL rupture group and 7.2 ± 3.2 mm in the complete ACL rupture group. In the quantitative measurements of pivot-shift test, the mean acceleration of the sudden reduction of the tibia in the knees with the intact contralateral ACL was -632.7 ± 254.5 mm/s^2, whereas it was -1107.5 ± 398.9 mm/s^2 in partial rupture group and -1652.2 ± 754.9 mm/s^2 in complete rupture group. Significant differences were detected between the three groups. In KT-1000 measurements, the mean side-to-side differences of anterior tibial translation were 3.8 ± 2.4 mm in the partial rupture group and 5.4 ± 2.3 mm in the complete rupture group. These investigators concluded that the quantitative assessments of knees with partial ACL injuries during the Lachman test and the pivot-shift test using the EMS showed less laxity than did knees with complete ACL injuries, whereas the knee laxity with partial ACL injuries was greater than the contralateral knees with intact ACLs. With respect to the function of the ACL remnant and the diagnosis of partial ACL injury, several remaining questions may be answered in the future with the use of EMS.

28.4 Arthroscopy

There are different diagnostic tools available in identifying a partial or complete ACL. However, exact injury pattern of anteromedial (AM) or posterolateral (PL) bundle tear can only be determined arthroscopically.

28.4.1 Evaluation by Arthroscopy

1. Arthroscopic intra-articular inspections is performed through the standard anteromedial portal or anterolateral portal. A thorough

arthroscopic probing is needed to precisely assess the ACL remnant patterns. Careful probing on the femoral side is important because most ACL ruptures occur in the proximal half of the ACL. An isolated PL bundle tear can easily be missed when viewing with standard arthroscopic visualization [2, 29, 30]. In this position, the PL bundle can only be seen by retraction of the AM bundle with a probe. In order to evaluate ACL remnant precisely, arthroscopic examination should be performed not only with standard arthroscopic visualization (90° of knee flexion) but also in a figure-of-4 position and also at various knee flexion angles [2, 4, 22, 30]. When the knee is placed in the figure-of-4 position, the PL bundle can be easily recognized [30, 31]. Evidence of bleeding and discontinuity are signs of rupture [2].

In patients with ACL injury, arthroscopic examination occasionally demonstrates a relatively thick and abundant ACL remnant maintaining a bridge between the tibia and either the intercondylar notch or posterior cruciate ligament (PCL). Even when the substantial remnant maintains a bridge between the intercondylar notch and the tibia, the femoral attachment of the ACL remnant is often positioned abnormally. These cases can represent a functionally complete ACL tear. However, sometimes there may be a preserved AM or PL bundle including an attachment of the anatomical femoral origin. Although these cases probably represent a partial rupture of the ACL, there is still controversy regarding the occurrence or definition of a partial rupture among arthroscopic surgeons. Partial rupture of the ACL has been recognized for many years [32, 33]. Noyes et al. [33] investigated 32 patients of partial ACL tear. Their definition of partial ACL tear was based on the percentage of ACL fibers torn. They excluded ACL tears involving more than 75 % of the ligament. In their study, 50 % of the patients with one-half of ligament fibers torn progressed to complete ACL tear, and 86 % of the patients with three-fourths of ligament fibers torn progressed to complete ACL tear. Lefevre et al. [19] reported that the ACL tear was defined as partial in case of a tear of one of the bundles on visual inspection and a remaining ligament which was still taut. We suspect partial ACL tear when the AM or PL bundle is preserved between the tibia and the anatomical femoral insertion of the ACL [11, 34].

A partial rupture of the ACL is observed in 10–28 % of isolated ACL lesions [6, 8, 21, 22, 29]. Colombet and Dejour et al. [6] reported that 27 % of their ACL injury cases showed partial rupture of the ACL. Zantop et al. [29] found a complete rupture of both the AM and PL bundles in 75 % of patients and a partial rupture of either the AM or PL bundle in 25 %. They not only examined the arthroscopic view of the injury pattern but also tested the functionality of the remaining ligament fibers. Sonnery-Cottet et al. reported that there were 21.2 % partial tears of the ACL, with 8.6 % being tears of the PL bundle and 12.6 % being tears of the AM bundle [22]. In our previous studies, the frequency of partial ACL tear was 10 % during the study period between 2002 and 2005 [8] and 20 % between 2006 and 2008[21]. After partial ACL tear, the ruptured bundle seems to retract toward the tibia over time [22, 35]. Sonnery-Cottet et al. [22] showed that individual PL bundle tears of the ACL retract with time. This retraction of the ruptured bundle appears to be a normal biologic reaction after ACL injury [36].

28.4.2 Classification of the ACL Remnant

A number of studies have classified the ACL remnant. Most of the studies concluded that the ACL remnant can contribute to biomechanical stability of the knee [5, 6, 21, 22, 24, 37]. Crain et al. [37] investigated a relationship between morphological pattern of ACL remnant and anterior laxity in 48 patients. The ACL remnants were divided into four categories according to ACL remnant morphology: ACL remnant scarring to the PCL (Group 1, 38 % of patients), ACL remnant scarring to the roof of the notch (Group 2, 8 %), ACL remnant scarring to the lateral wall of the notch in a position anterior and distal to the anatomic footprint of the ACL (Group 3, 12 %), and no identifiable ligament tissue remaining (Group 4, 42 %). The greatest increase in anterior laxity following resection of the remnant was observed in Group 3 (4.3 mm). It was also found that changes in anterior laxity were not related to time from injury to surgery. However, in their prospective study, there were no cases of partial ACL rupture in their 48 consecutive patients. It is possible they included patients with partial rupture of the AM or PL bundle in Group 2 or Group 3. Sonnery-Cottet et al. also commented that stump scarring to the lateral notch (Group 3, 12 % of the patients in the study be Crain et al.) may have been isolated bundle tears [22].

We also investigated morphological pattern of ACL remnant and knee laxity in 100 patients [21] (Fig. 28.1). This classification included partial rupture of the ACL. The ACL remnants were classified into five morphological patterns (Type 1, ACL remnant bridging the PCL and tibia; Type 2, ACL remnant bridging between the intercondylar notch and tibia; Type 3, partial rupture of the posterolateral bundle; Type 4, partial rupture of the anteromedial bundle; Type 5, no substantial ACL remnants). The percentage of patients in each ACL remnant pattern group was 18 %, 12 %, 14 %, 6 %, and 50 % for Groups 1, 2, 3, 4, and 5, respectively. The mean values of side-to-side difference in the KT-2000 arthrometer test were 6.1 mm, 5.7 mm, 3.3 mm, 3.0 mm, and 6.8 mm for Groups 1, 2, 3, 4, and 5, respectively. There was a statistically significant difference between partial rupture groups (Groups 3 and 4) and complete rupture groups (Groups 1, 2, and 5).

Colombet and Dejour et al. performed arthroscopic evaluation of the ACL rupture (a continuous series of 418 patients) [6]. They also included partial ACL tear in their classification. The ACL remnants were divided into four categories: totally disappeared ACL (50 %), posterolateral bundle conservation (16 %), healing on PCL (23 %), and anteromedial bundle conservation (11 %). In addition to the above classification, Dejour et al. subdivided the groups of partial ACL injury [5]. In the case of a partial ACL injury, further dynamic evaluation of the mechanical integrity of the remaining bundle was performed by palpation with a probe. The remaining bundle was classified as functional or nonfunctional, depending on the presence of mechanically solid fibers or the ability of the examiner to further stretch them, respectively. If the remaining bundle resisted further stretching, they were classified as functional. If the remaining bundle was lax and the examiner could stretch them significantly further, they were classified as nonfunctional. The authors found a significant difference between the occurrence of a functional remnant in the PL-intact group (functional, 67 %; nonfunctional, 33 %) and the occurrence of functional remaining fibers in the AM-intact and PCL-healing groups (functional, 17 %; nonfunctional, 83 %).

In order to determine the treatment strategy, Kazusa and Ochi et al. [34] classified the ACL remnant pattern as follows. Group 1 is partial rupture of the ACL (Group 1a, partial rupture of the PL bundle; Group 1b, partial rupture of the AM bundle; and Group 1c, partial rupture of the ACL but the remaining bundle could not be ascribed to either the AM or PL bundles). Group 2 is complete rupture of the ACL (Group 2a, ACL remnant bridging the PCL and tibia; Group 2b, ACL remnant bridging the roof of the intercondylar notch and tibia; Group 2c, ACL remnant bridging the lateral wall of the intercondylar notch and tibia; and Group 2d, no substantial ACL remnants bridging the tibia and either the femur or the PCL). Group 1a and Group 1b are indications for the single-bundle ACL augmentation. Group 1c, 2a, 2b, and 2c are indications for the single- or double-bundle ACL augmentation. Currently, we do not perform ACL augmentation for Group 2a.

In summary, although the diagnosis of a partial versus a complete ACL tear can be made with greater accuracy during arthroscopy, the decision as to whether the ACL remnant is preserved and ACL augmentation performed should be made after thorough consideration of clinical tests, laxity measurements, MRI, and arthroscopic findings.

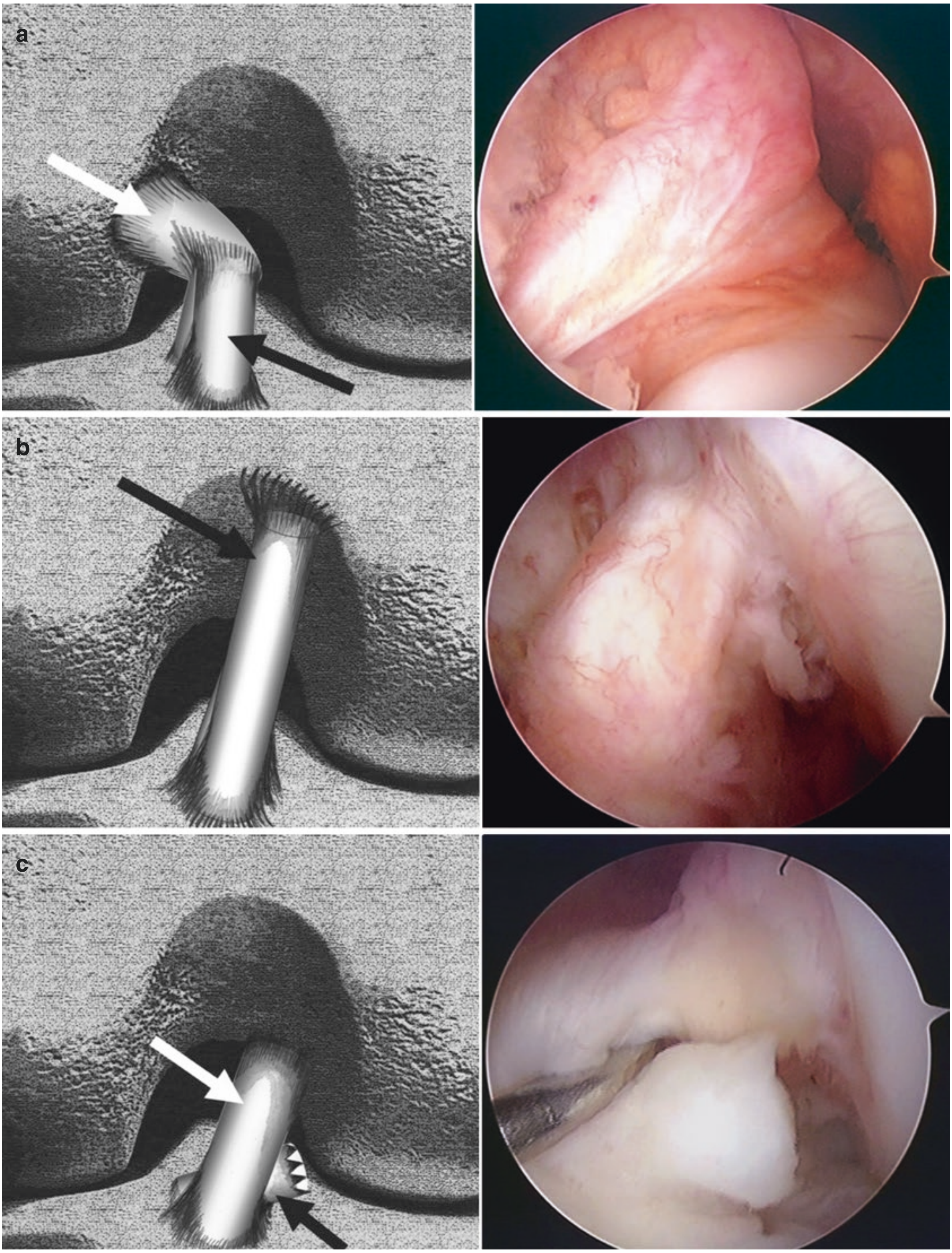

Fig. 28.1 Classification of the ACL remnant [21]. (**a**) Type 1: ACL remnant (*black arrow*) bridging the PCL (*white arrow*) and tibia. Normal attachment of the ACL to the femur was entirely lost. (**b**) Type 2: ACL remnant (*arrow*) bridging between the intercondylar notch and tibia. Normal attachment of the ACL to the femur was entirely lost. (**c**) Type 3: partial rupture of the posterolateral bundle (*black arrow*). The anteromedial bundle (*white arrow*) of the ACL has an attachment of femoral origin and is well preserved. (**d**) Type 4: partial rupture of the anteromedial bundle (*black arrow*). The posterolateral bundle (*white arrow*) of the ACL has an attachment of femoral origin and is well preserved. (**e**) Type 5: no substantial ACL remnants bridging the tibia and either the femur or PCL. The diameter of the proximal ACL remnant is attenuated to less than one-third of its original size, and the tension of the remnant is accordingly loose (*arrow*)

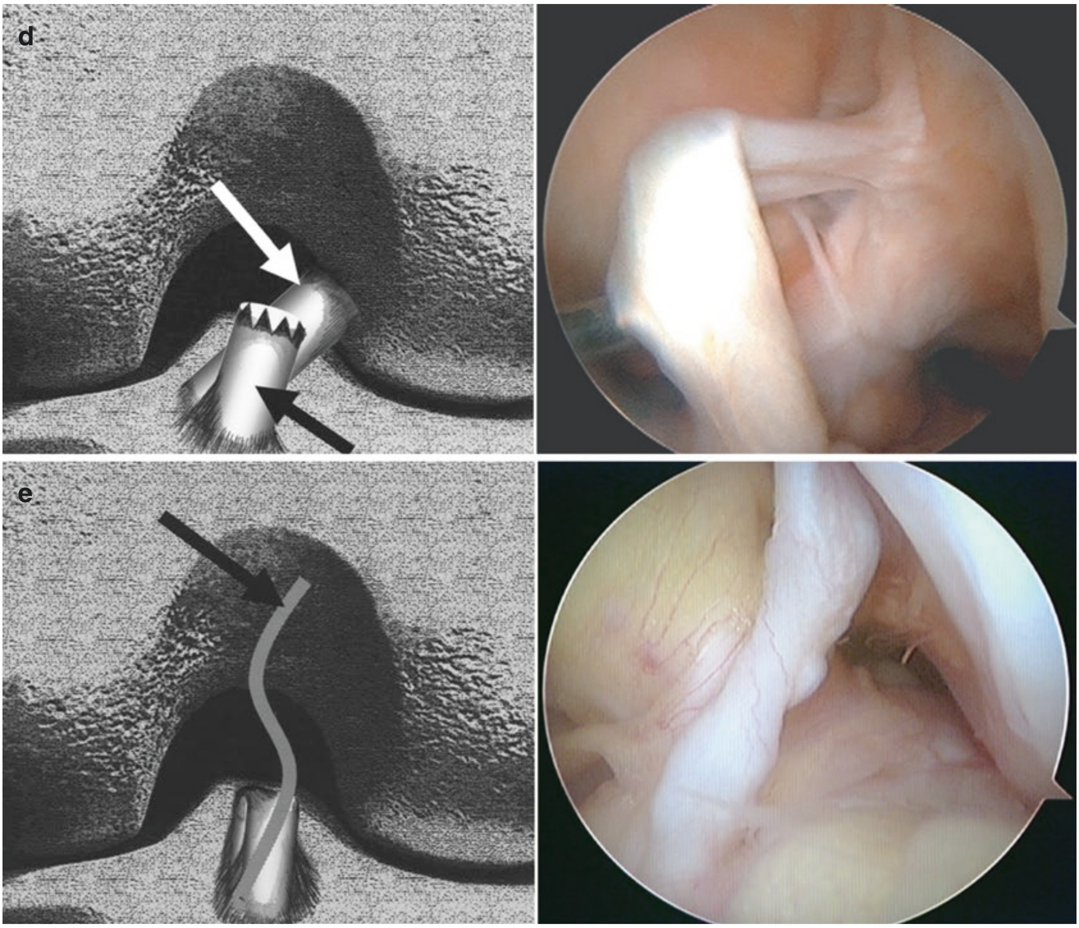

Fig. 28.1 (continued)

References

1. DeFranco MJ, Bach BR Jr (2009) A comprehensive review of partial anterior cruciate ligament tears. J Bone Joint Surg Am 91:198–208
2. Petersen W, Zantop T (2006) Partial rupture of the anterior cruciate ligament. Arthroscopy 22: 1143–1145
3. van Eck CF, Schreiber VM, Liu TT, Fu FH (2010) The anatomic approach to primary, revision and augmentation anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18:1154–1163
4. Siebold R, Fu FH (2008) Assessment and augmentation of symptomatic anteromedial or posterolateral bundle tears of the anterior cruciate ligament. Arthroscopy 24:1289–1298
5. Dejour D, Ntagiopoulos PG, Saggin PR, Panisset JC (2013) The diagnostic value of clinical tests, magnetic resonance imaging, and instrumented laxity in the differentiation of complete versus partial anterior cruciate ligament tears. Arthroscopy 29:491–499
6. Colombet P, Dejour D, Panisset JC, Siebold R, French Arthroscopy Society (2010) Current concept of partial anterior cruciate ligament ruptures. Orthop Traumatol Surg Res 96(8 Suppl):S109–S118
7. Van Dyck P, De Smet E, Veryser J et al (2012) Partial tear of the anterior cruciate ligament of the knee: injury patterns on MR imaging. Knee Surg Sports Traumatol Arthrosc 20:256–261
8. Ochi M, Adachi N, Deie M, Kanaya A (2006) Anterior cruciate ligament augmentation procedure with a 1-incision technique: anteromedial bundle or posterolateral bundle reconstruction. Arthroscopy 22:463.e1–e5
9. Ochi M, Adachi N, Uchio Y, Deie M, Kumahashi N, Ishikawa M, Sera S (2009) A minimum 2-year follow-up after selective anteromedial or posterolateral bundle anterior cruciate ligament reconstruction. Arthroscopy 25:117–122
10. Adachi N, Ochi M, Uchio Y, Sumen Y (2000) Anterior cruciate ligament augmentation under arthroscopy. A minimum 2-year follow-up in 40 patients. Arch Orthop Trauma Surg 120:128–133
11. Nakamae A, Ochi M, Deie M, Adachi N, Shibuya H, Ohkawa S, Hirata K (2014) Clinical outcomes of second-look arthroscopic evaluation after anterior cruciate ligament augmentation: comparison with

single- and double-bundle reconstruction. Bone Joint J 96-B:1325–1332

12. Gohil S, Annear PO, Breidahl W (2007) Anterior cruciate ligament reconstruction using autologous double hamstrings: a comparison of standard versus minimal debridement techniques using MRI to assess revascularisation. A randomised prospective study with a one-year follow-up. J Bone Joint Surg Br 89:1165–1171
13. Ahn JH, Lee SH, Choi SH, Lim TK (2010) Magnetic resonance imaging evaluation of anterior cruciate ligament reconstruction using quadrupled hamstring tendon autografts: comparison of remnant bundle preservation and standard technique. Am J Sports Med 38:1768–1777
14. Pujol N, Colombet P, Potel JF, Cucurulo T, Graveleau N, Hulet C, Panisset JC, Servien E, Sonnery-Cottet B, Trojani C, Djian P, French Arthroscopy Society (SFA) (2012) Anterior cruciate ligament reconstruction in partial tear: selective anteromedial bundle reconstruction conserving the posterolateral remnant versus single-bundle anatomic ACL reconstruction: preliminary 1-year results of a prospective randomized study. Orthop Traumatol Surg Res 98(8 Suppl):S171–S177
15. Demirağ B, Ermutlu C, Aydemir F, Durak K (2012) A comparison of clinical outcome of augmentation and standard reconstruction techniques for partial anterior cruciate ligament tears. Eklem Hastalik Cerrahisi 23:140–144
16. Zhang Q, Zhang S, Cao X, Liu L, Liu Y, Li R (2014) The effect of remnant preservation on tibial tunnel enlargement in ACL reconstruction with hamstring autograft: a prospective randomized controlled trial. Knee Surg Sports Traumatol Arthrosc 22:166–173
17. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R (1985) Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am 67:720–726
18. Daniel DM, Stone ML, Sachs R, Malcom L (1985) Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. Am J Sports Med 13:401–407
19. Lefevre N, Bohu Y, Naouri JF, Klouche S, Herman S (2014) Validity of GNRB® arthrometer compared to Telos™ in the assessment of partial anterior cruciate ligament tears. Knee Surg Sports Traumatol Arthrosc 22:285–290
20. Robert H, Nouveau S, Gageot S, Gagnière B (2009) A new knee arthrometer, the GNRB: experience in ACL complete and partial tears. Orthop Traumatol Surg Res 95:171–176
21. Nakamae A, Ochi M, Deie M, Adachi N, Kanaya A, Nishimori M, Nakasa T (2010) Biomechanical function of anterior cruciate ligament remnants: how long do they contribute to knee stability after injury in patients with complete tears? Arthroscopy 26:1577–1585
22. Sonnery-Cottet B, Barth J, Graveleau N, Fournier Y, Hager JP, Chambat P (2009) Arthroscopic identification of isolated tear of the posterolateral bundle of the anterior cruciate ligament. Arthroscopy 25:728–732
23. Maeda S, Ishibashi Y, Tsuda E, Yamamoto Y, Toh S (2011) Intraoperative navigation evaluation of tibial translation after resection of anterior cruciate ligament remnants. Arthroscopy 27:1203–1210
24. Nakase J, Toratani T, Kosaka M, Ohashi Y, Tsuchiya H (2013) Roles of ACL remnants in knee stability. Knee Surg Sports Traumatol Arthrosc 21:2101–2106
25. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 35:1098–1104
26. Araki D, Kuroda R, Kubo S, Nagamune K, Hoshino Y, Nishimoto K, Takayama K, Matsushita T, Tei K, Yamaguchi M, Kurosaka M (2011) The use of an electromagnetic measurement system for anterior tibial displacement during the Lachman test. Arthroscopy 27:792–802
27. Kuroda R, Hoshino Y, Araki D, Nishizawa Y, Nagamune K, Matsumoto T, Kubo S, Matsushita T, Kurosaka M (2012) Quantitative measurement of the pivot shift, reliability, and clinical applications. Knee Surg Sports Traumatol Arthrosc 20:686–691
28. Araki D, Kuroda R, Matsushita T, Matsumoto T, Kubo S, Nagamune K, Kurosaka M (2013) Biomechanical analysis of the knee with partial anterior cruciate ligament disruption: quantitative evaluation using an electromagnetic measurement system. Arthroscopy 29:1053–1062
29. Zantop T, Brucker PU, Vidal A, Zelle BA, Fu FH (2007) Intraarticular rupture pattern of the ACL. Clin Orthop Relat Res 454:48–53
30. Sonnery-Cottet B, Chambat P (2007) Arthroscopic identification of the anterior cruciate ligament posterolateral bundle: the figure-of-four position. Arthroscopy 23:1128.e1–3
31. Tejwani SG, Marx RG, Warren RF (2000) The figure-of-four view to evaluate ACL injury. Orthopedics 23(11):1153–1156
32. Liljedahl SO, Lindvall N, Wetterfors J (1965) Early diagnosis and treatment of acute ruptures of the anterior cruciate ligament; a clinical and arthrographic study of forty-eight cases. J Bone Joint Surg Am 47:1503–1513
33. Noyes FR, Mooar LA, Moorman CT 3rd, McGinniss GH (1989) Partial tears of the anterior cruciate ligament. Progression to complete ligament deficiency. J Bone Joint Surg Br 71:825–833
34. Kazusa H, Nakamae A, Ochi M (2013) Augmentation technique for anterior cruciate ligament injury. Clin Sports Med 32:127–140

35. Lo IK, de Maat GH, Valk JW, Frank CB (1999) The gross morphology of torn human anterior cruciate ligaments in unstable knees. Arthroscopy 15:301–306
36. Murray MM, Martin SD, Martin TL, Spector M (2000) Histological changes in the human anterior cruciate ligament after rupture. J Bone Joint Surg Am 82-A:1387–1397
37. Crain EH, Fithian DC, Paxton EW, Luetzow WF (2005) Variation in anterior cruciate ligament scar pattern: does the scar pattern affect anterior laxity in anterior cruciate ligament-deficient knees? Arthroscopy 21:19–24

ACL Augmentation

29

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29.1 Roles of Preserved ACL Remnant

There are three distinct reasons for which the preservation of ACL remnants may be beneficial for a successful ACL reconstruction.

The first reason is the biomechanical stability that may be enhanced by the presence of remnants. ACL remnants contribute to anteroposterior knee stability for up to 1 year after injury; however, beyond this time point, biomechanical function is lost [1].

Another reason that ACL should be retained during ACL reconstruction is the possible positive effect on the revascularization process. The vascular supply of the knee joint has been well described [2, 3]. The major supplying vessel of the intercondylar notch area, the human cruciate ligaments, and surrounding structures is the middle genicular artery [2, 3]. Prior studies have shown that the vascularization phase is one of the most important and sine qua non step in the ligamentization process [4, 5]. Revascularization of the substitute ACL graft occurs gradually along its length, with the intra-articular site being the first and the faster part to complete this phase, while both the intraosseous sites are still in progress throughout the first postoperative year [4]. Up to the second postoperative year, the intra-articular graft site reflected intense revascularization while a slower revascularization progress was noticed at the other two intraosseously enclosed sites [5]. Therefore the revascularization of the intra-articular part is an important link at the intrinsic healing chain of the ACL graft [4, 5]. In this context, the less damage of the ACL remnants that represent one of the important sites of the intra-articular native ACL part may be beneficial for the revascularization process.

The third reason for remnant preservation is the proprioception. It has been shown that in patients with ACL remnants adapted to the PCL, mechanoreceptors exist even 3 years after injury [6]. Since the restoration of proprioception is the result of reinnervation of the ACL, the preservation of ACL remnants as a source, if this is surgically possible without risk of a cyclops lesion, may be beneficial for the patient [6]. Actually, proprioceptive function was proved superior for patients with single-bundle (SB) augmentation reconstruction as compared to SB reconstruction at 6 and 12 months after surgery [7].

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Taken as a whole, relevant studies suggest that remnant-preserving ACL reconstruction would be favored for clinical and functional outcome since preservation of the ACL remnant may be beneficial in terms of proprioception, biomechanical functions, and vascularization of the graft. This evidence has influenced surgical techniques and remnant-preserving ACL reconstruction is used not only for partial rupture of the ACL but also for complete rupture.

29.2 ACL Augmentation Technique

29.2.1 Indications for ACL Augmentation

The decision as to whether the ACL remnant should be preserved and ACL augmentation performed is made after thorough consideration of clinical tests, laxity measurements, MRI, and arthroscopic findings [1, 8, 9]. Quantitative evaluation of anteroposterior knee laxity can aid in this decision. The patients are considered candidates for remnant-preserving ACL reconstruction when the side-to-side difference in the anterior displacement of the tibia is approximately less than 5 mm. MRI also provides important information regarding the condition of the proximal attachment of the ACL remnant. However, the final decision should be made after arthroscopic confirmation of the status of the injured ACL.

As stated in the former chapter (Diagnosis of Partial ACL Rupture), sometimes we encounter a partial rupture of the AM or PL bundle of the ACL during arthroscopy. Partial rupture of the ACL is an ideal indication for ACL augmentation. In these cases, single-bundle reconstruction of the ruptured bundle is desirable to preserve the femoral attachment of the remaining ACL bundle. In 2008, we began performing ACL augmentation even in patients with a continuous thick ACL remnant between the intercondylar notch and the tibia after complete rupture of the ACL. In this complete rupture group, the diameter of the proximal ACL remnant was greater than one-third of the original size and the femoral attachment of the ligamentous remnant was positioned abnormally. Anatomic central single-bundle or double-bundle [10] ACL reconstruction with the remnant-preserving technique is performed for the patients in this complete rupture group.

29.2.2 Surgical Technique

In this section, we describe surgical techniques of the single-bundle ACL augmentation as a standard procedure of remnant-preserving ACL reconstruction (Figs. 29.1 and 29.2). A four-strand gracilis and semitendinosus tendon or a quadrupled semitendinosus tendon is desirable as the graft for the augmentation. A three-portal technique (the anterolateral portal, the anteromedial portal, and the far-anteromedial portal) is used. The far-anteromedial portal is placed as inferior (close to the anterior portion of the medial meniscus) as possible, approximately 2.5 cm medial to the medial border of the patellar tendon.

29.2.2.1 Femoral Bone Tunnel

For femoral bone tunnel preparation, we regularly use the far-anteromedial portal technique, because this technique allows more flexibility in accurate anatomical positioning for femoral tunnel drilling than the transtibial technique. Excision of the femoral stump using a motorized shaver system is minimized. A delicate debridement and bone tunnel placement is important to minimize damage to the ACL remnant. It may be true that the main part of the femoral attachment of the ACL is on the resident's ridge from the biomechanical point of view, and the remaining part (fan-like extension fibers) is attached to the posterior portion of the ridge. However, we think that the center of the femoral tunnel opening should not be on the resident's ridge but should be placed just behind the resident's ridge when using the hamstring tendon for ACL reconstruction [9]. This is because the graft is pulled and shifts to the anterodistal side of the femoral tunnel opening in knee extension and mild flexion position. The center of the bone tunnel opening is not the central point of the application of force.

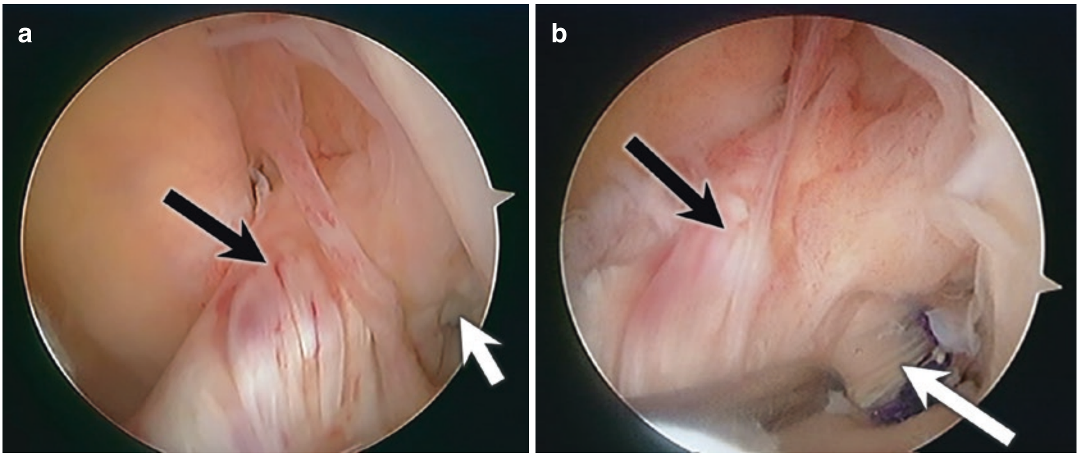

Fig. 29.1 (**a**) Partial rupture of the posterolateral (PL) bundle (*white arrow*). The anteromedial (AM) bundle (*black arrow*) of the ACL was well preserved although the remaining AM bundle is not completely intact. (**b**) AM bundle preserving ACL augmentation for the PL bundle rupture (*white arrow*, grafted tendon; *black arrow*, preserved AM bundle)

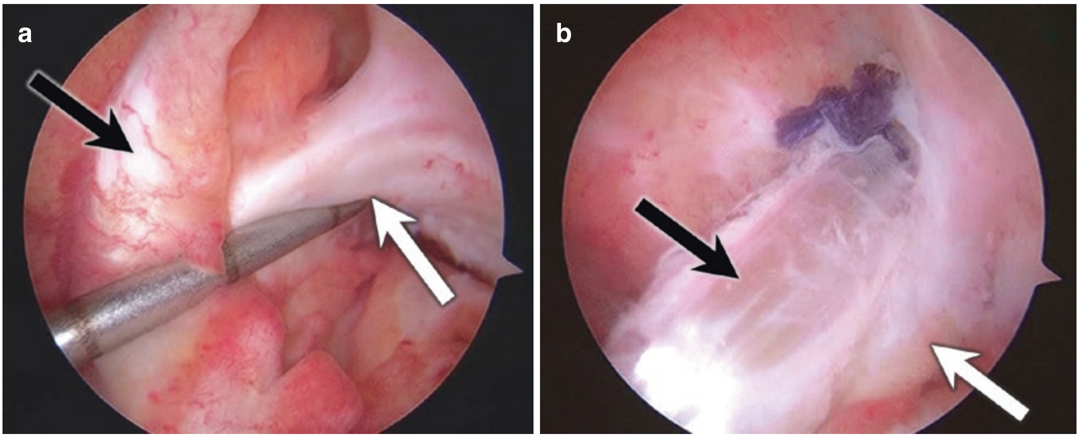

Fig. 29.2 (**a**) Partial rupture of the anteromedial (AM) bundle (*black arrow*). The posterolateral (PL) bundle (*white arrow*) of the ACL was preserved although the remaining PL bundle was not completely intact. (**b**) PL bundle preserving ACL augmentation for the AM bundle rupture (*black arrow*, grafted tendon; *white arrow*, preserved PL bundle)

In cases of PL bundle rupture, the central portion of the femoral tunnel is aimed at the clock position between 2 o'clock and 2:30 (left knee) or between 9:30 and 10 o'clock (right knee). At this position, approximately three-quarters of the femoral tunnel opening is occupied by the femoral attachment of the PL bundle and approximately one-quarter by the femoral attachment of the AM bundle. This is because we think that the remaining bundle is not intact and that the biomechanical function of the remaining bundle probably declines to some extent. In cases of AM bundle rupture, the central portion of the femoral tunnel was aimed at the clock position between 1:30 and 2 o'clock (left knee) or between 10 o'clock and 10:30 (right knee). In patients with a continuous thick ACL remnant between the intercondylar notch and the tibia after complete ACL rupture, the positions of the femoral bone tunnels is the same as used for standard anatomic single-bundle ACL reconstruction.

29.2.2.2 Tibial Bone Tunnel

In most cases, the tibial attachment of ACL remnant is normal. First, a longitudinal slit is made at the center of the ACL remnant through the anteromedial portal. The tip of the tibial drill guide, which is inserted through the anteromedial portal, is placed through the slit of the ACL remnant at an angle of 60–65° to the tibial plateau to allow visualization of the tip of the guide pin or Kirschner wire.

In cases of PL bundle rupture, the tip of the drill guide is positioned in the center of the tibial insertion of the whole ACL. In cases of AM bundle rupture and complete rupture, the tibial tunnel opening should be positioned as anterior as possible within the tibial footprint of the ACL. We recommend to check the position of the guide pin with the knee extended to see if the guide pin impinges on the roof of the intercondylar notch. When the position of the guide pin is satisfactory, the guide pin is advanced by a cannulated drill to create a tibial bone tunnel.

29.2.2.3 Graft Passage and Fixation

For cases such as the PL bundle rupture, if the graft passes above the ACL remnant, the positional relationship is anatomically incorrect. In such cases, pathologic impingement between the graft and the ACL remnant may occur. Therefore, in cases of PL bundle rupture and complete rupture, the graft should pass through the slit of the ACL remnant. As for the cases of AM bundle rupture, the graft should pass above the ACL remnant. The graft composites are introduced from the tibial tunnel to the femoral tunnel, and the proximal side of the graft is fixed to the lateral femoral cortex by flipping the endobutton. For graft fixation, we apply a tension force of 50 N to the distal endobutton tape connected to the graft and secure it with two staples at 30° of knee flexion.

29.3 Clinical Outcomes

29.3.1 Early History of ACL Augmentation

As detailed above, preserving the ACL remnant has great potential to contribute to knee function from several points of view. Therefore, in 1992, Ochi started performing ACL augmentation, when indicated, without sacrificing ACL remnant by using an autogenous hamstring tendon under arthroscopy. In 2000, Adachi et al. [11] reported that the proprioceptive function and joint stability of 40 patients who underwent arthroscopy-assisted ACL augmentation from 1992 to 1997 were superior to those of 40 patients who underwent standard single-bundle ACL reconstruction during the same period. However, in the early surgical procedure of ACL augmentation, the graft was passed through the over-the-top route for the femoral side. Therefore, the surgical technique needed two incisions at the medial aspect of the proximal tibia and also at the lateral femoral condyle. For this problem, Ochi started performing ACL augmentation with the one-incision technique using endobutton-CL and femoral bone tunnel and documented it as a report in 2006 [12]. The major indication for ACL augmentation was partial ACL rupture during the study period. In 2008, he started performing ACL augmentation even for patients with continuity of the ACL remnant between the femur and the tibia after complete ACL rupture. Anatomic central single-bundle ACL augmentation has been carried out for patients in this group.

29.3.2 Clinical Studies of ACL Augmentation

ACL augmentation has attracted much attention in the field of ACL reconstruction for this 10 years. Especially since 2006, a number of reports with regard to ACL augmentation has been published (Table 29.1) [13]. Several remnant-preserving techniques, including the remnant re-tensioning technique, selective AM or PL bundle reconstruction, and preservation of the ACL tibial remnant, have been described. To summarize the clinical results of ACL augmentation, we have reviewed the previous literature on ACL augmentation using a PubMed (1983–2014) and reported [13]. The review excluded case reports, literature review, animal studies, or current concepts. Table 29.1 [13] shows studies reporting arthroscopic remnant-preserving augmentation in ACL reconstruction. There are five different surgical techniques for ACL remnant preservation: (1) anatomic single-bundle ACL

Table 29.1 Studies reporting remnant-preserving augmentation in ACL reconstruction [13]

Study	Study design	Patient number[a]	Patient's age (years)[a]	Time from injury to reconstruction (months)[a]	Mean follow-up (months)[a]
Adachi and Ochi et al. (2000) [11]	Retrospective comparative study	40	25.8	4.2	38
Ochi et al. (2006) [12]	Technical note	17	31	Not reported	Not reported
Lee BI et al. (2006) [14]	Technical note	Not reported	Not reported	Not reported	Not reported
Buda et al. (2006) [15]	Case series	47	23.3	4.5	(More than 60)
Gohil et al. (2007) [16]	Randomized controlled trial	22	30.5	2	12
Buda et al. (2008) [17]	Case series	28	32.3	Not reported	27
Lee et al. (2008) [18]	Case series	16	35.1	5.5	35.1
Ochi et al. (2009) [8]	Case series	45	22	7.9	35
Yoon et al. (2009) [19]	Retrospective comparative study	82	28	7	24
Ahn et al. (2009) [20]	Technical note	65	Not reported	Not reported	Not reported
Kim et al. (2009) [21]	Technical note	21	Not reported	Not reported	12
Ahn et al. (2010) [22]	Cohort study	41	29.2	36.1	6.3
Sonnery-Cottet et al. (2010) [23]	Case series	36	32	6.6	24
Serrano-Fernandez et al. (2010) [24]	Case series	24	25	3	74
Ahn et al. (2011) [25]	Case series	53	32.2	28.2	27.7
Jung et al. (2011) [26]	Retrospective comparative study	76	32	2.5	31
Ochi et al. (2011) [10]	Technical note	Not reported	Not reported	Not reported	Not reported
Pujol et al. (2012) [27]	Randomized controlled trial	29	31.24	5.3	(More than 12)
Hong et al. (2012) [28]	Randomized controlled trial	39	34	10.3	25.8
Ohsawa et al. (2012) [29]	Case series	19	(15–57)	4.8	40.2
Yasuda et al. (2012) [30]	Case series	44	29	4	16.6
Park et al. (2012) [31]	Retrospective comparative study	55	30.4	7.0	34.1
Demirağ et al. (2012) [32]	Randomized controlled trial	20	28	2.3	24.3
Sonnery-Cottet et al. (2012) [33]	Case series	168	30	3	26

(continued)

Table 29.1 (continued)

Study	Study design	Patient number[a]	Patient's age (years)[a]	Time from injury to reconstruction (months)[a]	Mean follow-up (months)[a]
Cha et al. (2012) [34]	Retrospective comparative study	100	31.9	Not reported	Not reported
Muneta et al. (2013) [35]	Cohort study	88	22.1	6.7	(More than 24)
Kazusa and Ochi et al. (2013) [9]	Technical note	Not reported	Not reported	Not reported	Not reported
Maestro et al. (2013) [36]	Retrospective comparative study	39	28.1	1	31.7
Buda et al. (2013) [37]	Case series	52	23.3	4.3	(Up to 60)
Abat et al. (2013) [38]	Case series	28	30.4	2	37.3
Nakamae and Ochi et al. (2014) [39]	Retrospective comparative study	73	26.6	Not reported	28.9
Zhang et al. (2014) [40]	Randomized controlled trial	27	23.5	12.7	24.4
Lee et al. (2014) [41]	Retrospective comparative study	16	30.6	Not reported	29.5
Ahn et al. (2014) [42]	Technical note	Not reported	Not reported	Not reported	Not reported
Noh et al. (2014) [43]	Technical note	Not reported	Not reported	Not reported	Not reported
Sonnery-Cottet et al. (2014) [44]	Technical note	Not reported	Not reported	Not reported	Not reported
Muneta et al. (2014) [45]	Cohort study	200	Not reported	Not reported	Not reported
Kim et al. (2014) [46]	Retrospective comparative study	66	30	3	27
Taketomi et al. (2014) [47]	Technical note	47	31	4	Not reported

[a] Augmentation group only

augmentation preserving ACL remnant for complete rupture, (2) anatomic double-bundle ACL augmentation preserving ACL remnant for complete rupture, (3) single-bundle ACL reconstruction with remnant-tensioning technique, (4) selective AM or PL bundle augmentation for partial rupture, and (5) standard ACL reconstruction plus tibial remnant sparing. The ACL remnant in (1) and (2) maintains a bridge between the tibia and the intercondylar notch.

29.3.3 Clinical Outcomes of ACL Augmentation

Although there has been a growing interest in the potential advantages of ACL augmentation, a significant controversy remains regarding the use of remnant preservation techniques in ACL reconstruction. Thirteen clinical studies (Tables 29.2 and 29.3) [13] which compared the outcomes of ACL augmentation with those of the standard ACL reconstruction technique were selected from among studies in Table 29.1. Table 29.2 shows the characteristics of ACL remnant and type of graft in each study. Table 29.3 [13] shows clinical outcomes in each study. Several studies demonstrated favorable results using the ACL augmentation technique. Nakamae et al. report on the clinical outcomes and second-look arthroscopic findings of 216 patients who underwent ACL reconstruction (single or double bundle) or augmentation [39]. They concluded that patients in the ACL augmentation group exhibited better synovial

Table 29.2 Clinical studies which compared the ACL augmentation techniques with the standard ACL reconstruction technique [13]

Study	Conditions of ACL remnant for augmentation	Type of graft
Adachi and Ochi et al. (2000) [11]	ACL remnant bridging the femur and the tibia, with a diameter from one-third to one-half that of the normal ACL	Autogenous hamstring tendons or allogenic fascia lata
Gohil et al. (2007) [16]		Autologous hamstring tendons
Yoon et al. (2009) [19]	ACL remnant bridging the femur and the tibia anatomically, with a thickness of more than 50 % of that of the AM or PL bundle and laxity of less than 5 mm when drawn by a probe	Autologous hamstring tendons
Ahn et al. (2010) [22]	ACL remnant that could be tensioned toward the femoral bone tunnel	Autologous hamstring tendons
Pujol et al. (2012) [27]	Partial ACL tear; a well-inserted PL bundle	Autologous hamstring tendons or bone-patellar tendon bone
Hong et al. (2012) [28]	The remnant could be pulled to reach the femoral ACL insertion, and the remnant diameter was more than half of the native ACL	Allogeneic tibialis anterior or hamstring tendon
Park et al. (2012) [31]	Attachment of the remnant bundle between the femur and the tibia, the thickness of the ACL exceeding more than 50 % of that of the AM or PL bundle, and laxity of less than 5 mm when drawn by a probe	Autologous hamstring tendons
Demirağ et al. (2012) [32]	ACL remnant with more than one-half of its integrity preserved, bridging the tibia and the femur, and elongated no more than one-half of its length	Autologous hamstring tendons
Cha et al. (2012) [34]	ACL remnant that could be tensioned toward the femoral bone tunnel	Autologous hamstring tendons
Maestro et al. (2013) [36]	Partial ACL tear; a healthy bundle with a diameter equivalent to at least one-third of the original ACL was found, which was functional after palpation with a hook probe showing retention of its femoral and tibial insertions	Autologous hamstring tendons
Nakamae and Ochi et al. (2014) [39]	Partial rupture of the ACL; ligamentous fibers were seen to be in continuity from the femur to the tibia and the femoral attachment of those fibers was within the anatomical femoral insertion of the ACL	Autologous hamstring tendons
	Complete rupture of the ACL; thick ACL remnant (greater than one-third of the original size) maintaining a ligamentous bridge between the tibia and the femur and the femoral attachment of the ACL remnant was positioned non-anatomically	
Zhang et al. (2014) [40]		Autologous hamstring tendons
Lee et al. (2014) [41]	Partial ACL tear; there was a relatively intact bundle during surgery	Autologous hamstring tendons

AM anteromedial, *PL* posterolateral

Table 29.3 Outcomes in studies which compared the ACL augmentation techniques with the standard ACL reconstruction technique [13]

Study	The mean side-to-side difference in instrumented knee-laxity testing (anterior displacement of the tibia)	Pivot shift test (positive rate)	Other findings	Complications
Adachi and Ochi et al. (2000) [11]	0.7 mm in group A and 1.8 mm in group S ($P<0.05$)	8 % in group A and 4 % in group S (not significant)	Inaccuracy of joint position sense was 0.7° in group A and 1.7° in group S ($P<0.05$). ACL augmentation technique may contribute to restoring the proprioceptive function of the knee	
Gohil et al. (2007) [16]	3.2 (2–5) mm in group A and 2.75 (2–5) mm in group S		ACL augmentation technique appears to accelerate revascularization as indicated by increased signal intensity of MRI in the mid-substance of the graft at 2 months	No significant differences were found in incidence of cyclops lesions and ROM
Yoon et al. (2009) [19]	2.2 mm in group A and 1.9 mm in group S	12 % in group A and 12 % in group S		One case of limited ROM was observed in each group
Ahn et al. (2010) [22]			MRI showed significantly larger ACL grafts in group A than in group S, and these preserved remnant bundles showed progressive remodeling in the ACL graft	No significant difference was found in incidence of cyclops lesions
Pujol et al. (2012) [27]	1.24 mm in group A and 1.87 mm in group S ($P=0.03$)	17 % in group A and 28 % in group S ($P=0.4$)	There were no significant differences in subjective IKDC, KOOS, or Lysholm scores between the groups	One patient in group A developed a cyclops lesion
Hong et al. (2012) [28]	1.6 mm in group A and 1.8 mm in group S ($P=0.69$)	5 % in group A and 12 % in group S ($P=0.52$)	The passive angle reproduction test for proprioception measurements showed that there was no difference between both groups at final follow-up	In each group, cyclops lesion formation occurred in three patients
Park et al. (2012) [31]	1.5 mm in group A and 1.7 mm in group S (double bundle) ($P=0.69$)	9 % in group A and 11 % in group S (double bundle) ($P=0.74$)	There were no significant differences in the postoperative ROM, visual analog scale score, Lysholm score, Tegner score, and International Knee Documentation Committee knee evaluation form score between the two groups	

Demirağ et al. (2012) [32]		20 % in group A and 15 % in group S ($P=0.5$)	Tibial and femoral tunnel widening was less in the augmentation group. This difference was more significant on the tibial side	One patient in group A developed a cyclops lesion confirmed by MRI
Cha et al. (2012) [34]			Eight cyclops lesions (3/20 (15.0 %) in group S and 5/41 (12.2 %) in group A) were found in the 61 patients who underwent second look ($P=0.76$)	
Maestro et al. (2013) [36]	1.8 mm in group A and 2.3 mm in group S	13 % in group A and 36 % in group S		No postoperative complications
Nakamae and Ochi et al. (2014) [39]	0.4 mm in group A, 1.3 mm in single-bundle group, and 0.9 mm in double-bundle group ($P=0.013$ between group A and the single-bundle group)	12 % in group A, 21 % in single-bundle group, and 15 % in double-bundle group ($P=0.65$)	Second-look arthroscopy showed significantly better synovial coverage of the graft in group A than in the other groups. Improvement in proprioceptive function (threshold to detect passive motion) was seen in patients with good synovial coverage of the graft	
Zhang et al. (2014) [40]	1.4 mm in group A and 1.7 mm in group S (not significant)		The percentage of tibial tunnel enlargement was 25.7 % in group A and 34.0 % in group S ($P=0.0004$)	
Lee et al. (2014) [41]	1.8 mm in group A and 1.9 mm in group S (double bundle) (not significant)	6 % in group A and 6 % in group S (not significant)	No statistical differences in the Lysholm, Tegner, and International Knee Documentation committee scores were observed between the two groups	ROM was not statistically different between the groups

Group A ACL augmentation (remnant-preserving ACL reconstruction) group, *group S* standard ACL reconstruction technique group, *ROM* range of motion coverage of the graft upon second-look arthroscopy than those in the single- and double-bundle reconstruction groups. Improvement in proprioceptive function was observed in patients with good synovial coverage of the graft. With regard to the mean side-to-side difference measured using the KT-2000 arthrometer, a significant difference was found between the augmentation group (0.4 mm) and the single-bundle group (1.3 mm). However, three studies concluded that ACL augmentation had no evident advantage in clinical outcome over the standard single-bundle ACL reconstruction [19, 28, 40]. One of these studies used allografts from the tibialis anterior or hamstring tendon. Furthermore, in these three studies, the average preoperative side-to-side difference in anterior knee laxity in the augmentation group was relatively large and almost same with those in the standard single-bundle reconstruction group. Indications for and concept of ACL augmentation may have differed from studies.

Among the 13 clinical studies, ten studies [11, 16, 19, 27, 28, 31, 36, 39–41] evaluated the side-to-side difference in instrumented anterior knee-laxity testing. Three studies concluded that patients in the ACL augmentation group exhibited better anterior knee stability than those in the single-bundle reconstruction group [11, 27, 39]. The remaining seven studies reported that there was no significant difference between the groups of surgical technique at final follow-up. Out of the seven studies, two studies showed similar anteroposterior knee stability between the ACL augmentation group and double-bundle reconstruction group [31, 41]. Lee et al. [41] concluded that selective bundle ACL reconstruction could be performed instead of double-bundle ACL reconstruction if some intact bundle exists. Nine studies evaluated results of the pivot shift test, and ten studies reported data on the clinical scores. With regard to the pivot shift test and clinical scores, none of the studies indicated that there were significant differences between the groups at final follow-up.

The currently available evidence suggests that clinical outcomes of patients with the ACL augmentation technique are comparable with that of patients who underwent double-bundle ACL reconstruction. A significant controversy still remains regarding the clinical superiority of ACL augmentation compared to standard single-bundle ACL reconstruction. Although longer follow-up studies and further comparative clinical studies with a sufficient number of patients are necessary before a definitive conclusion can be reached, we think that ACL augmentation is a reasonable treatment option for patients with favorable ACL remnants.

References

1. Nakamae A, Ochi M, Deie M, Adachi N, Kanaya A, Nishimori M, Nakasa T (2010) Biomechanical function of anterior cruciate ligament remnants: how long do they contribute to knee stability after injury in patients with complete tears? Arthroscopy 26:1577–1585
2. Scapinelli R (1997) Vascular anatomy of the human cruciate ligaments and surrounding structures. Clin Anat 10(3):151–162
3. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J (2006) Anatomy of the anterior cruciate ligament. Knee Surg Sports Traumatol Arthrosc 14(3):204–213, Epub 2005 Oct 19
4. Ntoulia A, Papadopoulou F, Ristanis S, Argyropoulou M, Georgoulis AD (2011) Revascularization process of the bone – patellar tendon – bone autograft evaluated by contrast-enhanced magnetic resonance imaging 6 and 12 months after anterior cruciate ligament reconstruction. Am J Sports Med 39(7):1478–1486. doi:10.1177/0363546511398039, Epub 2011 Mar 10
5. Ntoulia A, Papadopoulou F, Zampeli F, Ristanis S, Argyropoulou M, Georgoulis A (2013) Evaluation with contrast-enhanced magnetic resonance imaging of the anterior cruciate ligament graft during its healing process: a two-year prospective study. Skeletal Radiol 42(4):541–552. doi:10.1007/s00256-012-1534-y, Epub 2012 Dec 11
6. Georgoulis AD, Pappa L, Moebius U, Malamou-Mitsi V, Pappa S, Papageorgiou CO, Agnantis NJ, Soucacos PN (2001) The presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL autograft. Knee Surg Sports Traumatol Arthrosc 9(6):364–368, Epub 2001 Sep 7
7. Ma Y, Deie M, Iwaki D, Asaeda M, Fujita N, Adachi N, Ochi M (2014) Balance ability and proprioception after single-bundle, single-bundle augmentation, and double-bundle ACL reconstruction. Sci World J 2014:342012. doi:10.1155/2014/342012.Epub2014Dec31.24.2and24.3
8. Ochi M, Adachi N, Uchio Y, Deie M, Kumahashi N, Ishikawa M, Sera S (2009) A minimum 2-year follow-up after selective anteromedial or posterolateral

bundle anterior cruciate ligament reconstruction. Arthroscopy 25:117–122

9. Kazusa H, Nakamae A, Ochi M (2013) Augmentation technique for anterior cruciate ligament injury. Clin Sports Med 32:127–140
10. Ochi M, Abouheif MM, Kongcharoensombat W, Nakamae A, Adachi N, Deie M (2011) Double bundle arthroscopic anterior cruciate ligament reconstruction with remnant preserving technique using a hamstring autograft. Sports Med Arthrosc Rehabil Ther Technol 3:30
11. Adachi N, Ochi M, Uchio Y, Sumen Y (2000) Anterior cruciate ligament augmentation under arthroscopy. A minimum 2-year follow-up in 40 patients. Arch Orthop Trauma Surg 120:128–133
12. Ochi M, Adachi N, Deie M, Kanaya A (2006) Anterior cruciate ligament augmentation procedure with a 1-incision technique: anteromedial bundle or posterolateral bundle reconstruction. Arthroscopy 22:463.e1–e5
13. Ochi M, Nakamae A (2016) History and advantages of ACL augmentation. In: Ochi M, Shino K, Yasuda K, Kurosaka M (eds) ACL injury and its treatment, 1st edn. Springer, Heidelberg, p. 335–348
14. Lee BI, Min KD, Choi HS, Kim JB, Kim ST (2006) Arthroscopic anterior cruciate ligament reconstruction with the tibial-remnant preserving technique using a hamstring graft. Arthroscopy 22:340.e1–e7
15. Buda R, Ferruzzi A, Vannini F, Zambelli L, Di Caprio F (2006) Augmentation technique with semitendinosus and gracilis tendons in chronic partial lesions of the ACL: clinical and arthrometric analysis. Knee Surg Sports Traumatol Arthrosc 14:1101–1107
16. Gohil S, Annear PO, Breidahl W (2007) Anterior cruciate ligament reconstruction using autologous double hamstrings: a comparison of standard versus minimal debridement techniques using MRI to assess revascularisation. A randomised prospective study with a one-year follow-up. J Bone Joint Surg Br 89:1165–1171
17. Buda R, Di Caprio F, Giuriati L, Luciani D, Busacca M, Giannini S (2008) Partial ACL tears augmented with distally inserted hamstring tendons and over-the-top fixation: an MRI evaluation. Knee 15:111–116
18. Lee BI, Kwon SW, Kim JB, Choi HS, Min KD (2008) Comparison of clinical results according to amount of preserved remnant in arthroscopic anterior cruciate ligament reconstruction using quadrupled hamstring graft. Arthroscopy 24:560–568
19. Yoon KH, Bae DK, Cho SM, Park SY, Lee JH (2009) Standard anterior cruciate ligament reconstruction versus isolated single-bundle augmentation with hamstring autograft. Arthroscopy 25:1265–1274
20. Ahn JH, Lee YS, Ha HC (2009) Anterior cruciate ligament reconstruction with preservation of remnant bundle using hamstring autograft: technical note. Arch Orthop Trauma Surg 129:1011–1015
21. Kim SJ, Jo SB, Kim TW, Chang JH, Choi HS, Oh KS (2009) A modified arthroscopic anterior cruciate ligament double-bundle reconstruction technique with autogenous quadriceps tendon graft: remnant-preserving technique. Arch Orthop Trauma Surg 129:403–407
22. Ahn JH, Lee SH, Choi SH, Lim TK (2010) Magnetic resonance imaging evaluation of anterior cruciate ligament reconstruction using quadrupled hamstring tendon autografts: comparison of remnant bundle preservation and standard technique. Am J Sports Med 38:1768–1777
23. Sonnery-Cottet B, Lavoie F, Ogassawara R, Scussiato RG, Kidder JF, Chambat P (2010) Selective anteromedial bundle reconstruction in partial ACL tears: a series of 36 patients with mean 24 months follow-up. Knee Surg Sports Traumatol Arthrosc 18:47–51
24. Serrano-Fernandez JM, Espejo-Baena A, Martin-Castilla B, De La Torre-Solis F, Mariscal-Lara J, Merino-Ruiz ML (2010) Augmentation technique for partial ACL ruptures using semitendinosus tendon in the over-the-top position. Knee Surg Sports Traumatol Arthrosc 18:1214–1218
25. Ahn JH, Wang JH, Lee YS, Kim JG, Kang JH, Koh KH (2011) Anterior cruciate ligament reconstruction using remnant preservation and a femoral tensioning technique: clinical and magnetic resonance imaging results. Arthroscopy 27:1079–1089
26. Jung YB, Jung HJ, Siti HT, Lee YS, Lee HJ, Lee SH, Cheon HY (2011) Comparison of anterior cruciate ligament reconstruction with preservation only versus remnant tensioning technique. Arthroscopy 27:1252–1258
27. Pujol N, Colombet P, Potel JF, Cucurulo T, Graveleau N, Hulet C, Panisset JC, Servien E, Sonnery-Cottet B, Trojani C, Djian P, French Arthroscopy Society (SFA) (2012) Anterior cruciate ligament reconstruction in partial tear: selective anteromedial bundle reconstruction conserving the posterolateral remnant versus single-bundle anatomic ACL reconstruction: preliminary 1-year results of a prospective randomized study. Orthop Traumatol Surg Res 98(8 Suppl):S171–S177
28. Hong L, Li X, Zhang H, Liu X, Zhang J, Shen JW, Feng H (2012) Anterior cruciate ligament reconstruction with remnant preservation: a prospective, randomized controlled study. Am J Sports Med 40:2747–2755
29. Ohsawa T, Kimura M, Kobayashi Y, Hagiwara K, Yorifuji H, Takagishi K (2012) Arthroscopic evaluation of preserved ligament remnant after selective anteromedial or posterolateral bundle anterior cruciate ligament reconstruction. Arthroscopy 28:807–817
30. Yasuda K, Kondo E, Kitamura N, Kawaguchi Y, Kai S, Tanabe Y (2012) A pilot study of anatomic double-bundle anterior cruciate ligament reconstruction with ligament remnant tissue preservation. Arthroscopy 28:343–353
31. Park SY, Oh H, Park SW, Lee JH, Lee SH, Yoon KH (2012) Clinical outcomes of remnant-preserving augmentation versus double-bundle reconstruction in the anterior cruciate ligament reconstruction. Arthroscopy 28:1833–1841
32. Demirağ B, Ermutlu C, Aydemir F, Durak K (2012) A comparison of clinical outcome of augmentation and

standard reconstruction techniques for partial anterior cruciate ligament tears. Eklem Hastalik Cerrahisi 23:140–144

33. Sonnery-Cottet B, Panisset JC, Colombet P, Cucurulo T, Graveleau N, Hulet C, Potel JF, Servien E, Trojani C, Djian P, Pujol N, French Arthroscopy Society (SFA) (2012) Partial ACL reconstruction with preservation of the posterolateral bundle. Orthop Traumatol Surg Res 98(8 Suppl):S165–S170
34. Cha J, Choi SH, Kwon JW, Lee SH, Ahn JH (2012) Analysis of cyclops lesions after different anterior cruciate ligament reconstructions: a comparison of the single-bundle and remnant bundle preservation techniques. Skeletal Radiol 41:997–1002
35. Muneta T, Koga H, Ju YJ, Horie M, Nakamura T, Sekiya I (2013) Remnant volume of anterior cruciate ligament correlates preoperative patients' status and postoperative outcome. Knee Surg Sports Traumatol Arthrosc 21:906–913
36. Maestro A, Suárez-Suárez MA, Rodríguez-López L, Villa-Vigil A (2013) Stability evaluation after isolated reconstruction of anteromedial or posterolateral bundle in symptomatic partial tears of anterior cruciate ligament. Eur J Orthop Surg Traumatol 23:471–480
37. Buda R, Ruffilli A, Parma A, Pagliazzi G, Luciani D, Ramponi L, Castagnini F, Giannini S (2013) Partial ACL tears: anatomic reconstruction versus nonanatomic augmentation surgery. Orthopedics 36:e1108–e1113
38. Abat F, Gelber PE, Erquicia JI, Pelfort X, Tey M, Monllau JC (2013) Promising short-term results following selective bundle reconstruction in partial anterior cruciate ligament tears. Knee 20:332–338
39. Nakamae A, Ochi M, Deie M, Adachi N, Shibuya H, Ohkawa S, Hirata K (2014) Clinical outcomes of second-look arthroscopic evaluation after anterior cruciate ligament augmentation: comparison with single- and double-bundle reconstruction. Bone Joint J 96-B:1325–1332
40. Zhang Q, Zhang S, Cao X, Liu L, Liu Y, Li R (2014) The effect of remnant preservation on tibial tunnel enlargement in ACL reconstruction with hamstring autograft: a prospective randomized controlled trial. Knee Surg Sports Traumatol Arthrosc 22:166–173
41. Lee YS, Nam SW, Sim JA, Lee BK (2014) Comparison of anatomic ACL reconstruction between selective bundle reconstruction and double-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc 22:2803–2810
42. Ahn JH, Lee YS, Lee SH (2014) Creation of an anatomic femoral tunnel with minimal damage to the remnant bundle in remnant-preserving anterior cruciate ligament reconstruction using an outside-in technique. Arthrosc Tech 3:e175–e179
43. Noh JH, Yoon KH, Song SJ, Roh YH (2014) Re-tensioning technique to cover the graft with remnant in anterior cruciate ligament reconstruction. Arthrosc Tech 3:e679–e682
44. Sonnery-Cottet B, Freychet B, Murphy CG, Pupim BH, Thaunat M (2014) Anterior cruciate ligament reconstruction and preservation: The Single-Anteromedial Bundle Biological Augmentation (SAMBBA) technique. Arthrosc Tech 3:e689–e693
45. Muneta T, Koga H, Nakamura T, Horie M, Watanabe T, Yagishita K, Sekiya I (2015) A new behind-remnant approach for remnant-preserving double-bundle anterior cruciate ligament reconstruction compared with a standard approach. Knee Surg Sports Traumatol Arthrosc 23(12):3743–3749
46. Kim MK, Lee SR, Ha JK, Ra HJ, Kim SB, Kim JG (2014) Comparison of second-look arthroscopic findings and clinical results according to the amount of preserved remnant in anterior cruciate ligament reconstruction. Knee 21:774–778
47. Taketomi S, Inui H, Sanada T, Nakamura K, Yamagami R, Masuda H, Tanaka S, Nakagawa T (2014) Remnant-preserving anterior cruciate ligament reconstruction using a three-dimensional fluoroscopic navigation system. Knee Surg Relat Res 26:168–176

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Allografts in Anterior Cruciate Ligament Reconstruction

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30.1 Introduction

Injuries to the anterior cruciate ligament (ACL) are common with a reported case load of over 200,000 reconstructions performed in the United States annually [1]. Reconstruction of the ligament is frequently performed to restore anterolateral stability to the knee in order to prevent further intraarticular damage from repeated pivoting episodes and to return athletes to competitive play [2, 3]. Typical choices for grafts that are used for reconstruction purposes are autografts which include bone-patellar tendon-bone, hamstring, and quadriceps tendons and allografts which come from a variety of sources. Examples of allograft materials are patellar tendon (with and without bone blocks), Achilles tendon, tibialis anterior, tibialis posterior, and quadriceps tendons.

Traditionally, allograft tissue has been favored for ACL reconstruction because it allowed for a much more rapid and easier procedure. In addition, due to the absence of donor site morbidity that is inherent with the use of autograft materials, the patient is likely to experience much less pain subsequent to surgery which may in turn accelerate progress during rehabilitation. However, a majority of studies investigating the long-term viability of allograft tissue have demonstrated a significant failure rate in the younger population [4, 5]. Evidence from basic science investigations have revealed that allografts undergo a similar “ligamentization” process as autografts when implanted into the knee. However, the replacement of the donor tissue with host synovial cells is much slower when compared with reconstructions using autografts, which may help to explain the fact that allografts typically demonstrate inferior biomechanical properties as autografts during the healing phase [6]. These findings have limited the use of allografts in this patient population, and most surgeons now prefer to utilize allografts in the older, less active population among whom the risk of graft rupture is comparatively less.

Despite these concerns, allografts remain a popular choice for ACL reconstruction in the proper setting. The following chapter will detail the common indications and methods of processing for allografts and review the current literature regarding the outcomes related to their use.

30.2 Indications

The prevailing concept that allograft tissue is significantly weaker than autograft tissue has led to a decrease in the use of this graft choice in the

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younger, athletic population. Nevertheless, the choice of allograft may be considered in the setting of primary ACL reconstruction. Older patients electing to proceed with ACL reconstruction are more likely to receive allografts as it is generally believed that these patients will progress more slowly through the rehabilitation phases, thereby reducing the stress on the implanted graft and allowing for additional time for healing. This trend is supported by the 2013 AOSSM report on allograft usage in ACL surgery, which revealed that the allocation of allografts by surgeons is predominantly aimed at patients in the 35–40 year range [7].

The choice to utilize allografts for the purpose of reconstruction may also be influenced by settings in which there is insufficient autograft tissue for harvest, such as in cases that require the surgeon to address multiple injured ligaments, cases where the intended autograft harvested is too small for use, or in cases of revision ACL reconstruction. When addressing multiligamentous knee injuries, the need for additional collagen often makes the use of autograft tissue impractical given the significant morbidity inherent in extracting graft material as well as the scarcity of available tissue. Multiligamentous knee injuries may include ruptures to the posterior cruciate ligament and posterolateral corner. While repair of the posterolateral corner remains an accepted form of treatment during acute intervention, the stability of direct repair has been questioned, and evidence has suggested that more reliable stability can be obtained by augmentation with allograft [8, 9]. In such cases, to reduce the morbidity to the knee that has already experienced significant injury and to reduce overall surgical time, the surgeon may be more inclined to reconstruct the ACL with allograft tissue.

Another common scenario that may require allograft use is under circumstances when the intended autograft tissue is estimated to be too small to effectively reconstruct the ACL. This is often encountered during the use of hamstring autografts. Past studies have noted that the threshold diameter for the hamstring graft that is associated with lower rerupture rates is approximately 8 mm [10, 11]. Not infrequently, the diameter of the hamstrings may be smaller than this threshold. For this reason, allograft material may be combined with the hamstring autograft to create a composite graft. This technique can significantly enhance the diameter of the graft above the 8 mm threshold, increasing the stability of the soft tissue reconstruction.

Finally, it is common for consideration to be given to allograft material when performing revision ACL reconstruction. Due to tunnel dilation that may occur as a consequence of the primary ACL reconstruction, the tissue available for autograft may be insufficient to accommodate the larger tunnel diameter, particularly if the intended graft is bone-patellar-tendon-bone or hamstring tendon. In addition, if the primary surgery was performed using autograft material, the preferred autograft may not be present for use during the revision surgery. Allografts provide a solution to both problems by providing the surgeon with a variety of graft types with a wide range of dimensions to fit bone tunnels that have expanded since the index operation. The use of allografts also affords flexibility in terms of graft size during revision cases, with larger allografts granting the advantage of favorable time-zero strength when stability of the graft is a concern. Because of these properties intrinsic to allograft materials, studies have supported the idea that a greater proportion of surgeons do elect to utilize this type of graft for revision ACL reconstruction. According to a report by the Multicenter ACL Revision Study group, approximately 54 % of surgeons participating in the study chose to perform a revision ACL reconstruction with an allograft compared to 27 % of surgeons who used allograft for primary ACL reconstruction [12].

30.3 Procurement

The handling of allogeneic material is overseen by the combined effort of both the organ procurement organizations (OPOs) and the tissue banks. In North America a nationwide network of OPOs acts as central coordinating agency for tissue donation. The OPOs, as members of the Organ Procurement Transplant Network, are responsible for tissue and organ recovery and distribution within a predefined service area. After evaluation and screening for potential donors, the OPOs arrange the surgical removal of the donated tissue. The tissue banks on the other hand are primarily responsible for the tissue procurement process. The tissue banks follow the quality instructions and standards of the Food and Drug Administration (FDA) and American Association of Tissue Banks (AATB). A trained donor coordinator obtains consent from the patient or the family and provides information how the donated tissue is going to be used [13].

Great care is taken to ensure that maximum sterility of grafts is achieved once they are considered ready for use. Most tissue banks mandate that grafts be harvested no more than 24 hours from death for refrigerated grafts and no more than 12 hours from death for cadavers stored at room temperature [14]. Prior to harvest, the tissue donor must be screened for human immunodeficiency virus (HIV), hepatitis B, and hepatitis C. Frequently, the tissues are aseptically harvested in the operating room or morgue. However, the tissue extracted in this manner should not be considered sterile, since aseptic processing minimizes but does not obviate tissue contamination [13, 15]. The grafts are then passed through a process of decontamination.

Understanding the phases of procurement requires an awareness of the meaning behind disinfection, which is interpreted as the elimination of contamination, and sterilization, which is interpreted as the total extermination of all life forms [16]. The FDA currently does not require sterilization of medically appropriate grafts. In fact, a sterility assurance level (SAL) of 10^{-6} is recommended during the decontamination process to maximally reduce the risk of disease transmission. This threshold level is understood to mean that the risk that a microorganism might survive the decontamination process is less than 1 in 1,000,000.

In order to attain this quality of sterilization, different mechanical and chemical processes have been developed over the years. The use of gaseous ethylene oxide as sterilizing agent has been abandoned due to its immunogenic effects, reported adverse events, and poor tissue penetration [13]. In general, initial graft treatment typically consists of chemical decontamination with a series of antibiotic solutions. This method however does not lead to sterilization of the graft. A very common method of mechanical sterilization is the use of ionizing radiation (gamma irradiation). To eliminate HIV an irradiation dose of 35–40 kGy is required. However, this dosage leads to collagen breakdown with significant deterioration of the biomechanical and structural properties of the processed graft properties [17]. Therefore, many tissue banks use lower irradiation doses between 10 and 25 kGy [18]. However, these irradiation doses are effective against bacteria but less effective against viruses [13]. Because of the disadvantages of both mechanical and chemical treatments, modern methods for graft decontamination elect to utilize a hybrid approach to achieve a level close to sterilization as possible. The combination of both chemical and mechanical processing methods (i.e., BioCleanse®, Allowash®) showed initially promising results [19], but a cohort study with more than 5,000 participants found a significantly increased risk of graft failure and subsequent revision surgery when the graft was treated with BioCleanse® [20].

The use of nonirradiated allografts is becoming more popular due to their superior biomechanical and biological properties. Many recent studies have demonstrated the clinical effectiveness of nonirradiated allografts, particularly in reducing the incidence of graft rupture [21, 22]. One example is the use of freeze-dried grafts (lyophilized tissue). During the lyophilization process, the moisture content of the graft is reduced to less than 5 % and needs therefore to be rehydrated before use. In the recent years, fresh-frozen allografts have been most commonly used. After sterile tissue harvesting and culturing, the graft is frozen while serologic tests performed. Before packaging the graft is soaked in an antibiotic solution and can be stored at −80 °C for 3–5 years [16, 23].

It is clear that the procurement process plays a vital role in the overall clinical performance of

ACL reconstruction with allograft materials. However, a majority of orthopedic surgeons who perform this procedure remain unaware of the graft processing methods for the allografts they utilize. A survey of 236 hospitals in the United States reported that only 34 % of orthopedic surgeons performing allograft-related surgeries were familiar with the tissue processing history [24]. In addition, in only 15 % of the facilities surveyed did the orthopedic surgeon directly contribute to the type of allograft selected. This data highlights a significant problem in the use of allografts for surgery, particularly in the case of ACL reconstruction in which the concerns regarding graft longevity may be profoundly influenced by the variability in procurement methods.

30.4 Clinical Outcomes

There have been many studies comparing the short-term outcomes of ACL reconstruction with autografts and allografts in patients. Early studies were favorable toward the use of allografts. Shino et al. published a study with 84 patients after ACL reconstruction with allografts with an average follow-up of 57 months [25]. The patient population was relatively young with an average age of 22 years old and there was no evidence of immunologic rejection. Subjective and functional outcomes were good with 57 % of patients having "excellent" outcomes, 37 % with "good" outcomes, and only 2 % with "fair" outcomes [25]. Objective physical exams also found that 88 % of patients had satisfactory anterior stability, though 3 % of patients did have a reinjury. Noyes et al., while preferring autografts, also found allografts to be a justifiable substitute since they could find no significant difference in anterior-posterior displacement, patellofemoral crepitus, pain, jumping score, or overall knee rating [26].

Other studies directly compared allografts to autografts. While allografts were rarely shown to perform better than the gold standard autograft, there was evidence to show that outcomes following surgery with each type of graft were comparable. Rihn et al. found no significant differences in average International Knee Documentation Committee (IKDC) subjective knee scores between patients who received irradiated bone-patellar tendon-bone allografts (BTB) and BTB autografts ($P=0.65$) [27]. There were also no significant differences in the percentage of patients in each cohort that reported a normal/nearly normal overall IKDC physical examination rating ($P=0.37$) or that returned to the same or more strenuous level of sports ($P=0.25$) [27].

Stringham et al. also reached a similar conclusion that allografts are a suitable substitute for autografts [28]. They compared 47 patients with BTB autografts and 31 patients with BTB allografts who were evaluated at an average of 34 months post-surgery. There were no significant differences in subjective outcomes (measured using Lysholm and Tegner knee scores), patellofemoral signs and symptoms, laxity differences, single-leg hop scores, or isokinetic results [28]. However, there was a significantly greater number of ruptures in the allograft group. Stringham et al. had four allograft ruptures an average of 11 months following surgery and no autograft ruptures [28].

Several other studies comparing autograft and allograft cohorts also found few significant differences in subjective and objective outcomes following surgery with allografts and autografts [29–33]. A meta-analysis by Krych et al. also found no significant differences between the two groups for many measures including pivot shift test, patellofemoral crepitus, return to pre-injury activity level, and IKDC scores [34]. They did, however, find a significantly higher incidence of graft ruptures in the allograft group [34]. A second meta-analysis, from Prodromos et al. found that allografts were less stable than autografts and had higher rates of failure, a conclusion that aligns with the conclusions in Barrett et al.'s study that found greater laxity in allografts [35, 36].

Finally, Bottoni et al. recently published a randomized controlled trial with 10-year follow-up comparing treatment with allografts to treatment with autografts [37]. Patients were randomized to either the hamstring autograft group or the tibialis posterior allograft group. Similar to Stringham et al. and Prodromos et al., Bottoni et al. found a greater than three times higher rate of graft failure in the allograft group compared to the autograft group [37]. However, functional outcomes measured using the single assessment numeric evaluation, Tegner, or IKDC scores were similar between the two groups.

Overall, the studies lead to the conclusion that while reconstruction with autografts may be the preferred treatment, allografts are still an acceptable substitute, especially since results have been shown to be comparable between the two. However, the literature also demonstrates a few key differences that are important to note and consider when choosing a graft.

30.4.1 Graft Rupture and Failure

The most significant concern about allograft usage would be the evidence of a greater risk of graft rupture and failure. It has already been noted that Stringham et al., Prodromos et al., and Bottoni et al. all found a higher rate of failures in allografts [28, 35, 37]. Chang et al. also found the same trend, reporting three ruptures in the allograft group and none in the autograft group [29].

Other recent studies have also focused on the issue of higher failure rates in allografts, especially in a young, athletic patient population [38]. A multicenter prospective cohort study by Kaeding et al. found graft type to be a significant predictor of graft failure. The odds of an allograft rupturing were four times greater than those for an autograft [4]. Furthermore, the risk of graft rupture increased 2.3 times for each 10-year decrease in age. This is likely at least in part due to younger patients being more active. Lenehan's study came to similar conclusions and recommended that patients less than 25 years of age should not receive allograft reconstructions [39]. Finally, Tejwani et al.'s study, notable for its very large sample size of 5,968, also found that younger patients were at greater risk of revision [20].

30.4.2 Pain and Recovery

Since allografts do not need to be harvested from the patient, this technique results in less pain for the patient. Poehling et al. conducted a prospective comparative case series that compared 41 patients who received an Achilles tendon allograft to 118 patients who underwent BTB autograft reconstruction [40]. The patients were followed for 5 years, and it was found that autograft patients reported significantly more pain for the first 6 weeks according to both the RAND 36-Item Health Survey and the McGill Pain Scale [40]. A higher proportion of patients in the allograft group also reported normal or nearly normal knee function at 3 months ($P=0.0558$), fewer activity limitations at 6 months ($P=0.0014$), and more laxity in KT-1000 measurements ($P=0.0520$) [40].

Barrett et al. found no significant difference in pain between allograft and autograft groups, but they did find that patients who received allografts returned to sport sooner, with 57 % of patients in the allograft group returning to sport in 6 months compared to only 25 % of the autograft group [36]. Though allografts may be more likely to rupture than autografts, these findings indicate that it may still be a good choice for an individual who is not very active, and therefore has a lower risk of graft rupture, since they will have less pain and can resume activities faster.

30.4.3 Logistical Benefits

The cost of allograft relative to the cost of an autograft is also greater, as the autograft is free of charge. However, the overall cost of allograft reconstructions has actually been found to be lower than costs for autograft reconstructions [34]. Cole et al. found that the average cost for an allograft procedure in a sample of 122 patients treated at a hospital in the Southern United States was $4,622, while the average cost for an autograft procedure was $5,694 ($P<0.0001$) [41]. The authors attributed the decreased cost of allograft reconstructions to shorter operating room time and a greater likelihood of overnight hospitalization for patients who had autograft procedures [41].

However, Nagda et al. also performed a cost analysis of both graft types for ACL reconstruction and concluded that if all surgeries were completed in an outpatient setting, such as an ambulatory care center, autograft surgeries would be cheaper ($4,872 for autograft versus $5,465 for allograft) [42]. They determined that the higher cost of supplies for allograft procedures exceeds the cost saved by shorter operating times.

Depending on the setting, whether outpatient or inpatient, the cost of the procedure is another consideration to take into account when deciding on graft choice. However, it should be noted that these two studies did not look at the lifetime cost of each procedure, which would also take into account rehabilitation costs and the higher risk of rupture and revision for allografts.

Conclusion

Allografts are an attractive option for ACL reconstruction because of clinical benefits such as the lack of donor site morbidity, multiple options for sizing, and diminished pain following surgery. In some cases where redundant collagen is required, such as in revision ACL reconstruction or treatment of multiligamentous knee injuries, the use of allograft is ideal. However, evidence continues to suggest that the risk of rerupture after ACL reconstruction for patients receiving allografts remains higher than if the reconstructions were performed with autograft tissue, making the choice of allograft a secondary option for primary ACL reconstruction in the younger population. When electing to use allografts, orthopedic surgeons should consider the source of the tissue at their disposal as processing methods may influence the clinical effectiveness of the implanted graft.

References

1. Gottlob CA, Baker CL, Pellissier JM, Colvin L (1999) Cost effectiveness of anterior cruciate ligament reconstruction in young adults. Clin Orthop Relat Res 367:272–282
2. Heijink A, Gomoll AH, Madry H, Drobnič M, Filardo G, Espregueira-Mendes J, Van Dijk CN (2012) Biomechanical considerations in the pathogenesis of osteoarthritis of the knee. Knee Surg Sports Traumatol Arthrosc 20(3):423–435
3. Maletius W, Messner K (1999) Eighteen- to twenty-four-year follow-up after complete rupture of the anterior cruciate ligament. Am J Sports Med 27(6):711–717
4. Kaeding CC, Aros B, Pedroza A, Pifel E, Amendola A, Andrish JT, Dunn WR, Marx RG, McCarty EC, Parker RD, Wright RW, Spindler KP (2011) Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health 3(1):73–81
5. Bottoni CR, Smith EL, Shaha J, Shaha SS, Raybin SG, Tokish JM, Rowles DJ (2015) Autograft versus allograft anterior cruciate ligament reconstruction: a prospective, randomized clinical study with a minimum 10-year follow-up. Am J Sports Med 43(10):2501–2509
6. Jackson DW, Simon TM, Kurzweil PR, Rosen MA (1992) Survival of cells after intra-articular transplantation of fresh allografts of the patellar and anterior cruciate ligaments. DNA-probe analysis in a goat model. J Bone Joint Surg Am 74(1):112–118
7. Allografts for ACL reconstruction survey report. American Academy of Orthopaedic Surgeons (AAOS) Department of Research and Scientific Affairs (2013), pp 1–73. https://www.sportsmed.org/AOSSMIMIS/members/downloads/research/AllograftACLReconstructionSurveyReport.pdf
8. Levy BA, Dajani KA, Morgan JA, Shah JP, Dahm DL, Stuart MJ (2010) Repair versus reconstruction of the fibular collateral ligament and posterolateral corner in the multiligament-injured knee. Am J Sports Med 38(4):804–809
9. Stannard JP, Brown SL, Farris RC, McGwin G Jr, Volgas DA (2005) The posterolateral corner of the knee: repair versus reconstruction. Am J Sports Med 33(6):881–888
10. Boniello MR, Schwingler PM, Bonner JM, Robinson SP, Cotter A, Bonner KF (2015) Impact of hamstring graft diameter on tendon strength: a biomechanical study. Arthroscopy 31(6):1084–1090
11. Conte EJ, Hyatt AE, Gatt CJ, Dhawan A (2014) Hamstring autograft size can be predicted and is a potential risk factor for anterior cruciate ligament reconstruction failure. Arthroscopy 30(7):882–890
12. MARS Group, Wright RW, Huston LJ, Spindler KP, Dunn WR, Haas AK, Allen CR, Cooper DE, DeBerardino TM, Lantz BB, Mann BJ, Stuart MJ (2010) Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. Am J Sports Med 38(10):1979–1986
13. Vangsness CT Jr, Garcia IA, Mills CR, Kainer MA, Roberts MR, Moore TM (2003) Allograft transplantation in the knee: tissue regulation, procurement, processing, and sterilization. Am J Sports Med 31(3):474–481
14. Vangsness C, Triffon M, Joyce M, Moore T (1996) Soft tissue for allograft reconstruction of the human knee: a survey of the American Association of Tissue Banks. Am J Sports Med 24:230–234
15. Vangsness CT Jr (2006) Soft-tissue allograft processing controversies. J Knee Surg 19(3):215–219
16. McAllister DR, Joyce MJ, Mann BJ, Vangsness CT (2007) Allograft update: the current status of tissue regulation, procurement, processing, and sterilization. Am J Sports Med 35:2148–2158

17. Fideler BM, Vangsness CT Jr, Lu B, Orlando C, Moore T (1995) Gamma irradiation: effects on biomechanical properties of human bone-patellar tendon-bone allografts. Am J Sports Med 23(5):643–646
18. Robertson A, Nutton RW, Keating JF (2006) Current trends in the use of tendon allografts in orthopaedic surgery. J Bone Joint Surg Br 88(8):988–992
19. Indelicato PA, Ciccotti MG, Boyd J, Higgins LD, Shaffer BS, Vangsness CT Jr (2013) Aseptically processed and chemically sterilized BTB allografts for anterior cruciate ligament reconstruction: a prospective randomized study. Knee Surg Sports Traumatol Arthrosc 21:2107–2112
20. Tejwani SG, Chen J, Funahashi TT, Love R, Maletis GB (2015) Revision risk after allograft anterior cruciate ligament reconstruction: association with graft processing techniques, patient characteristics, and graft type. Am J Sports Med 43(11):2696–2705
21. Lamblin CJ, Waterman BR, Lubowitz JH (2013) Anterior cruciate ligament reconstruction with autografts compared with non-irradiated, non-chemically treated allografts. Arthroscopy 29(6):1113–1122
22. Mariscalco MW, Magnussen RA, Kaeding CC, Hewett TE, Flanigan DC (2014) Use of irradiated and non-irradiated allograft tissue in anterior cruciate ligament reconstruction surgery. J Bone Joint Surg Rev 2(2):e4
23. Busam ML, Rue JPH, Bach BR Jr (2007) Fresh-frozen allograft anterior cruciate ligament reconstruction. Clin Sports Med 26:607–623
24. Lavernia C, Malinin T, Temple H, Moreyra C (2004) Bone and tissue allograft use by orthopaedic surgeons. J Arthroplasty 19(4):430–435
25. Shino K, Inoue M, Horibe S, Hamada M, Ono K (1990) Reconstruction of the anterior cruciate ligament using free tendon graft. Am J Sport Med 18(5):457–465
26. Noyes FR, Barber-Westin SD (1996) Reconstruction of the anterior cruciate ligament with human allograft. Comparison of early and later results. J Bone Joint Surg Am 78(4):524–537
27. Rihn JA, Irrgang JJ, Chhabra A, Fu FH, Harner CD (2006) Does irradiation affect the clinical outcome of patellar tendon allograft ACL reconstruction? Knee Surg Sport Traumatol Arthrosc 14(9):885–896
28. Stringham D, Pelmas C, Burks R, Newman A, Marcus R (1996) Comparison of anterior cruciate ligament reconstructions using patellar tendon autograft or allograft. Arthroscopy 12(4):414–421
29. Chang SK, Egami DK, Shaieb MD, Kan DM, Richardson AB (2003) Anterior cruciate ligament reconstruction: allograft versus autograft. Arthroscopy 19(5):453–462
30. Shelton WR, Papendick L, Dukes AD (1997) Autograft versus allograft anterior cruciate ligament reconstruction. Arthroscopy 13(4):446–449
31. Peterson RK, Shelton WR, Bomboy AL (2001) Allograft versus autograft patellar tendon anterior cruciate ligament reconstruction: a 5-year follow-up. Arthroscopy 17(1):9–13
32. Kleipool AE, Zijl JA, Willems WJ (1998) Arthroscopic anterior cruciate ligament reconstruction with bone-patellar tendon-bone allograft or autograft. A prospective study with an average follow up of 4 years. Knee Surg Sport Traumatol Arthrosc 6(4):224–230
33. Saddemi SR, Frogameni AD, Fenton PJ, Hartman J, Hartman W (1993) Comparison of perioperative morbidity of anterior cruciate ligament autografts versus allografts. Arthroscopy 9(5):519–524
34. Krych AJ, Jackson JD, Hoskin TL, Dahm DL (2008) A meta-analysis of patellar tendon autograft versus patellar tendon allograft in anterior cruciate ligament reconstruction. Arthroscopy 24(3):292–298
35. Prodromos C, Joyce B, Shi K (2007) A meta-analysis of stability of autografts compared to allografts after anterior cruciate ligament reconstruction. Knee Surg Sport Traumatol Arthrosc 15(7):851–856
36. Barrett G, Stokes D, White M (2005) Anterior cruciate ligament reconstruction in patients older than 40 years allograft versus autograft patellar tendon. Am J Sport Med 33(10):1505–1512
37. Bottoni CR, Smith EL, Shaha J et al (2015) Autograft versus allograft anterior cruciate ligament reconstruction: a prospective, randomized clinical study with a minimum 10-year follow-up. Am J Sport Med 43(10):2501–2509
38. Nelson IR, Chen J, Love R, Davis BR, Maletis GB, Funahashi TT (2016) A comparison of revision and rerupture rates of ACL reconstruction between autografts and allografts in the skeletally immature. Knee Surg Sport Traumatol Arthrosc 24(3):773–779
39. Lenehan EA, Payne WB, Askam BM, Grana WA, Farrow LD (2015) Long-term outcomes of allograft reconstruction of the anterior cruciate ligament. Am J Orthop 44(5):217–222
40. Poehling GG, Curl WW, Lee CA et al (2005) Analysis of outcomes of anterior cruciate ligament repair with 5-year follow-up: allograft versus autograft. Arthroscopy 21(7): 774–785
41. Cole DW, Ginn TA, Chen GJ et al (2005) Cost comparison of anterior cruciate ligament reconstruction: autograft versus allograft. Arthroscopy 21(1526–3231): 786–790
42. Nagda SH, Altobelli GG, Bowdry KA, Brewster CE, Lombardo SJ (2010) Cost analysis of outpatient anterior cruciate ligament reconstruction: autograft versus allograft. Clin Orthop Relat Res 468(5): 1418–1422

Synthetic Ligaments for ACL Reconstruction

31

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31.1 Introduction

The clinical application of artificial ligaments in the anterior cruciate ligament (ACL) reconstruction is controversial. The potential advantages include a lack of graft harvest morbidity and the potential for the patient to make an early return to activity, including sports. For the athlete, the possibilities offered by a synthetic ligament appear attractive. Although first tried more than 100 years ago [14], there have essentially been two waves of publications regarding the use of artificial ligaments. The first related to devices implanted in the late 1970s and 1980s and reported poor outcomes including high failure rates and significant complications such as synovitis, osteolysis, and osteoarthritis. In recent years, there have been numerous publications regarding one specific and more modern device, with a number reporting satisfactory outcomes in the short- to midterm.

31.2 Early Synthetic Ligament Devices

31.2.1 Carbon Fiber

A number of carbon fiber devices were developed in the late 1970s, and there was considerable interest in the potential of carbon fiber as a scaffold for ligament regeneration [5, 8, 13–15]. However, high failure rates, synovitis, and dissemination of carbon fiber to regional lymph nodes [15, 18, 32] lead to the abandonment of carbon fiber as a basis for synthetic ligaments.

31.2.2 Dacron

The Dacron artificial ligament was made of polyester and designed as an augmentation. It was nonetheless used by some surgeons as a prosthetic ligament in "salvage" cases. Despite initial promising results, longer-term follow-up showed high failure rates, osteolysis, synovitis, and high rates of osteoarthritis [1, 2, 19], and the device was subsequently withdrawn from the market.

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31.2.3 Gore-Tex

The Gore-Tex artificial ligament was made of expanded polytetrafluoroethylene. As a permanent implant, an important property was its ultimate tensile strength of approximately 5,300 N, higher than any other counterparts. However, once again initial promising results were overtaken by poor outcomes in the midterm, with ligament failure and effusion being the predominant adverse findings [6, 20, 27, 28, 36]. Importantly, positioning of the graft was recognized as important with regard to the risk of graft abrasion and failure. The device was eventually withdrawn from the market.

31.2.4 Kennedy Ligament Augmentation Device

The Kennedy Ligament Augmentation Device (LAD) a ribbonlike construct made from polypropylene yarn was conceived and sutured to an autograft to form a composite graft. It was supposed that the LAD could protect the autograft during its remodeling, and it was assumed that potential stress shielding of the autograft would be minimized by the relatively low tensile strength of the LAD and the fact that only one end of device was fixed. Studies failed to show any advantage over autografts alone, and failures with intra-articular debris and effusions were reported [7, 11, 21]. As a result, usage of the Kennedy LAD ceased.

31.2.5 Leeds-Keio

The Leeds-Keio synthetic ligament was woven from polyester and was intended to serve as a scaffold for ingrowth of ligamentous tissue. Conflicting results with regard to ingrowth and clinical outcome were reported, and concerns were raised about the presence of foreign body giant cells containing polyester debris [17, 23, 30]. Like other synthetic ligaments, the Leeds-Keio ligament fell into disuse.

31.3 Current Synthetic Ligament Devices

There are two currently available synthetic ligament devices. One is the Ligament Augmentation Reinforcement System (Surgical Implants and Devices, Arc-sur-Tille, France), and the other is the JewelACL (Neoligaments, Leeds, England), for which there is currently no published literature.

The Ligament Augmentation Reinforcement System (LARS) is made from polyethylene terephthalate (PET) (Fig. 31.1). During manufacturing it is subjected to a cleaning process designed to remove residues and oils and thereby reduce the risk of synovitis and encourage tissue ingrowth. The intra-articular portion of the LARS is woven parallel to PET fibers that are pre-twisted

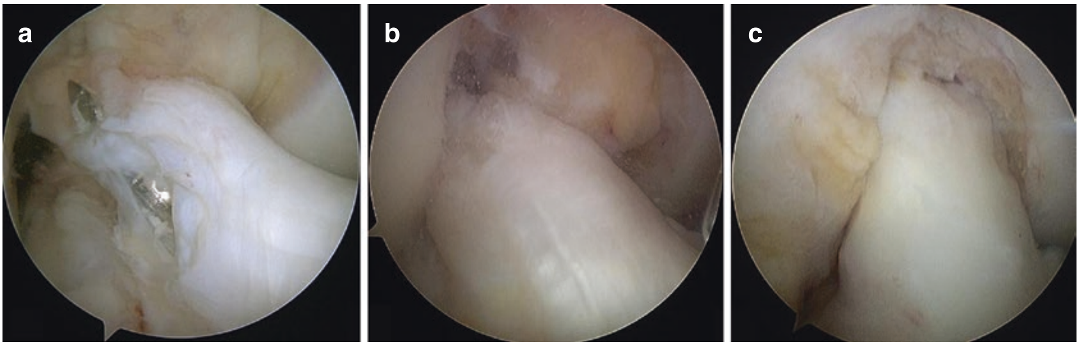

Fig. 31.1 ACL reconstruction with LARS device. (**a**) The ACL stump is intact. (**b**) The reconstruction is complete, with the LARS device is inside the stump. Some fibers of the LARS ligament are still exposed proximally. (**c**) 1-year postoperative second look, the LARS ligament is totally covered with soft tissue

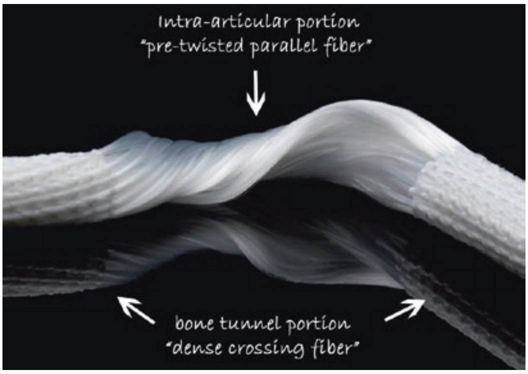

Fig. 31.2 The LARS device showing the pre-twisted parallel fibers of the intra-articular portion (Source: http://www.coringroup.com)

to 90° (Fig. 31.2). The remainder of this chapter will largely focus on the use and results of the LARS device.

31.4 Systematic Reviews

In 2011 Mulford et al. evaluated the efficacy of PET artificial ligaments in the ACL reconstruction [22]. A total of 23 papers published between 1970 and 2010 were included. Twelve papers were related to the LARS, and the remaining 11 focused on the long-term outcomes of other PET ligaments. In studies of the LARS, the mean follow-up period was 28 months (range 4–60 months). In 655 cases, documented graft rupture occurred in 14 cases (2 %). However, the poor methodological quality of the included studies was of concern.

In a 2013 systematic review that included many of the papers included in the review by Mulford et al., Newman et al. evaluated studies related to the ACL reconstruction with the LARS device [24]. There were nine papers, including one randomized control trial, and all were published between 1990 and 2010. The outcome demonstrated a similar failure rate of 2.5 %. Most failures were attributed to tunnel malposition. Again, only one case of synovitis was reported. Return to sports took 2–6 months, earlier than that for patients having an autograft procedure. However, the poor methodological quality of the papers and the need for high-quality longer-term studies were once again highlighted.

More recently, Batty et al. systematically reviewed the reports related to the clinical application of artificial ligaments in the cruciate ligament surgery [3]. With regard to the ACL, the highest failure rate was observed with the Dacron device with a cumulative failure rate of 33.6 %. Noninfective synovitis and effusion were most frequently seen with the Gore-Tex artificial ligament (up to 27.6 %). In contrast, the reported outcomes of the LARS device appeared encouraging.

Thirteen LARS ACL patient cohorts were identified, with 19 documented failures in 736 patients (2.6 %). In those studies, which reported Lysholm scores, the mean postoperative score was 88, compared to a mean preoperative score of 54. KT-1000 arthrometer side-to-side difference was measured in seven studies in 394 knees with a mean side-to-side difference of 2.2 mm (range, 1.2–4.2 mm). Pivot shift was recorded for 497 patients in four studies with a grade 2 pivot (clear shift and visible reduction) present in 6.4 %. There was only one reported case noninfective effusion or synovitis (Figs. 31.3, 31.4, 31.5, and 31.6).

In terms of comparative studies, the one RCT compared 26 LARS devices with 27 patellar tendon autografts. At 24 months there was no significant difference between the groups in terms of IKDC or KOOS scores. One retrospective study compared 30 patellar tendon autografts with 32 LARS reconstructions with a minimum follow-up of 4 years. There was no difference between the groups in terms of Lysholm, Tegner, IKDC, and KT-1000 assessments. In a second retrospective study, 32 four-strand hamstring ACL reconstructions were compared with 28 LARS ACL reconstructions, also with a minimum follow-up of 4 years. Again, there was no difference in Lysholm, IKDC, or Tegner scores, but the LARS group had significantly less anterior displacement as measured by KT-1000.

In the Batty et al. review, the MINORS score was used to assess the methodological quality of included studies. The ideal score was 16 points for non-comparative studies and case series and

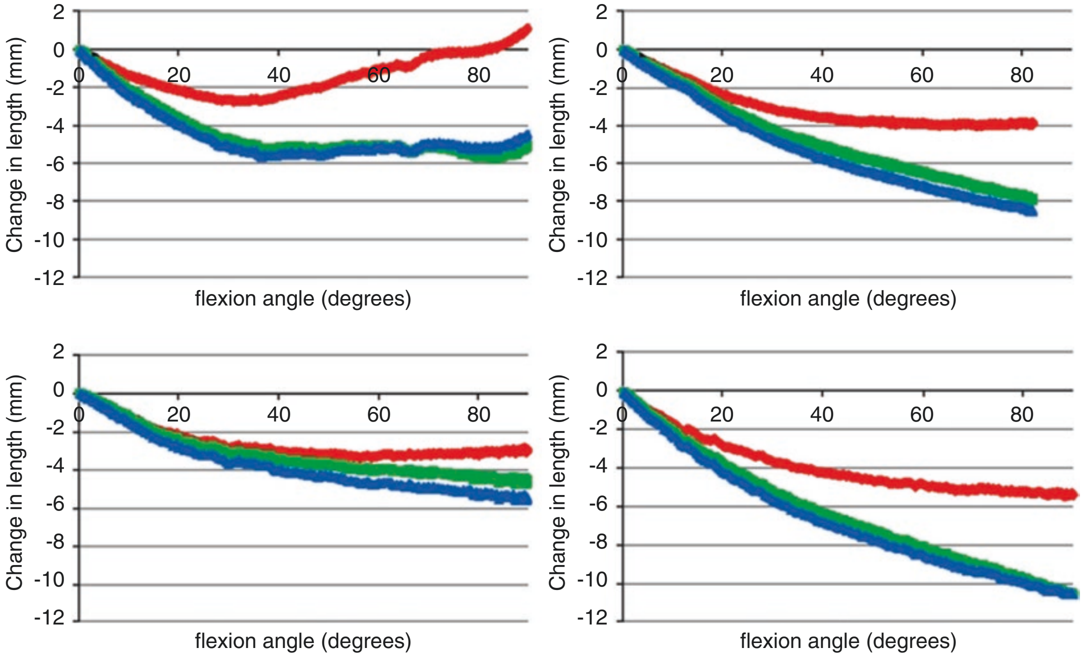

Fig. 31.3 Change in graft length of four specimens over a 90° flexion cycle, *red* is J. P. Laboureau, *green* is Bernard Hertel, and *blue* is Charlie Brown. Different GTM is noticed in different specimens. J. P. Laboureau's femoral point is the most isometric (Source: Danè Dabirrahmani et al. Computers in Biology and Medicine 43(2013)2287–2296)

24 points for comparative studies. The mean MINORS score for the included non-comparative LARS studies was only 7.6 points (SD, 1.2 points) and 17.3 points (SD, 1.5 points) for the comparative studies. The authors noted that in view of the low levels of evidence, the findings of the systematic review should be interpreted with caution. In addition, the potential for publication bias – whereby poor outcomes are less likely to be reported – should also be noted.

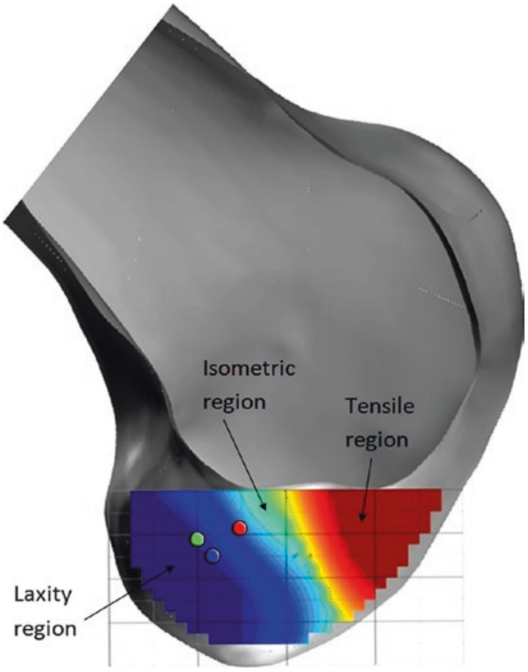

Fig. 31.4 A color contour plot showing regions on the Bernard Hertel grid where graft would undergo potential tension (*red* regions) and laxities (*blue* regions). *Red dot* is J. P. Laboureau, *green dot* is Bernard Hertel, and blue dot is Charlie Brown. J. P. Laboureau's point is the closest one to the isometric region (Source: Danè Dabirrahmani et al. Computers in Biology and Medicine 43(2013)2287–2296)

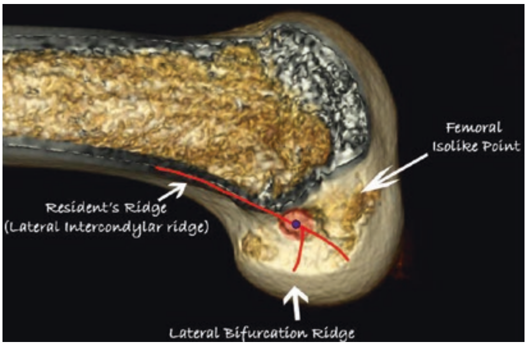

Fig. 31.5 The medial aspect of the femoral lateral condyle is shown on sagittal view. The bony mark of resident ridge which is the elongation of the posterior cortical line can always easily be exposed. The bifurcation ridge is sometimes visible around the middle point of the resident ridge. The femoral tunnel was positioned on the residential ridge and 1 mm posterior to the bifurcation ridge (*blue dot*). The *red circle* is the aperture of the femoral tunnel

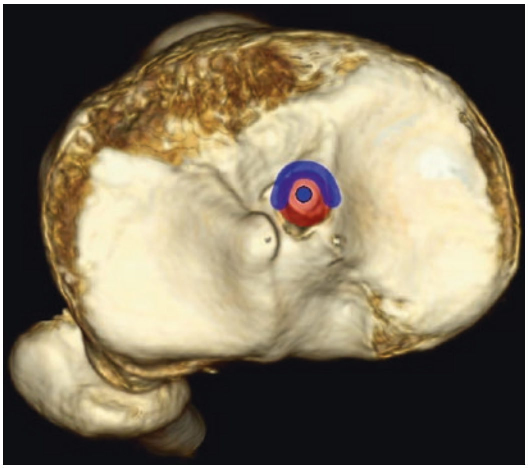

Fig. 31.6 The superior aspect of the tibial plateau is shown on axial view. The real ACL tibial footprint is usually C-shape (*blue area*). The tibial isolike point (*blue dot*) is 2 mm posterior to the *middle* point of the remnant in center of the “C-arm.” The *red circle* is the aperture of the tibial tunnel

31.5 Conflicting Results

In spite of the generally satisfactory results reported for the LARS in the above systematic reviews, questions remain about its role. Indeed, in many countries it has either not been approved for use, is not available, or has fallen from favor. In the following section, selected longer-term studies of the LARS are critically evaluated to highlight the varied results.

Parchi et al. reported on 26 of 29 patients a mean follow-up of 7.9 years [26]. The mean age of the patients at the time of follow-up was 38.5 years. Joint stability and range of motion were reported to be satisfactory in 24 patients. For the KOOS score, 11 patients (42.3 %) rated optimal (>90) and 13 (50 %) good [25–33]. However, there was a wide range of scores, from 10 to 100. Similar findings were found for the Cincinnati knee-rating scale with 92.3 % rating optimal (61.5 %) or good (30.8 %). Again, there was a wide range from 22 to 100.

The salient points for this study are that there was no control group; the patients were relatively older compared to the usual group reported in the follow-up of ACL reconstruction and elected to have a LARS procedure (potential for selection bias); despite generally satisfactory outcomes, some patients did badly, and no data regarding return to pre-injury activities was provided. It is to be noted that the authors conservatively concluded that the LARS device might be a “suitable option for ACL reconstruction in carefully selected cases, especially for older patients needing a fast functional recovery.”

However, in a more recent study, Tiefenboeck et al. came to the conclusion that the LARS device should “not be suggested as a potential graft for the primary reconstruction of the ACL” [33]. Twenty-six patients underwent primary isolated ACL reconstruction with the LARS between 2000 and 2004. The final evaluation was completed in 18 at the mean age of 29 years, with a mean follow-up period of 151 months. The high failure rate was the authors’ principal source of concern. Eleven patients had either KT-2000 side-to-side difference in anterior knee laxity of more than 5 mm (four patients) or a revision procedure due to reinjury (five patients) or revision due to deep infection (two patients).

Hamido et al. reported on the use of the LARS as an augmentation for small diameter or short-hamstring tendon autografts in 112 patients with a mean age of 26 years at the time of surgery

[12]. The follow-up period was 45 months. Relatively little detail about postoperative assessment is provided. However, on IKDC evaluation 67 % patients rated normal and 28.6 % rated nearly normal. Eighty-two percent of patients returned to their pre-injury sports activities. No patient had a graft rupture, synovitis, screw loosening, or bone tunnel enlargement on radiological examination.

31.6 Synovitis

Synovitis was a major concern with earlier synthetic grafts and was associated with osteoarthritis in the longer term [27, 31, 34] Klein. It was attributed to abrasion and breakage of the synthetic devices resulting in free debris and particles within the joint [Greis, Olsen]. It was felt that malposition of bone tunnels would hasten this process [Olsen]. There was a concern that because of the nonabsorbable nature of the synthetic ligaments, there was an increased risk of developing osteoarthritis.

It is therefore important to note that many studies of the LARS device report minimal or no problems with synovitis [3]. However, some instances of disabling synovitis have nonetheless been reported [10].

31.7 The Chinese Experience

Chinese surgeons did not experience the wave of enthusiasm for nor the subsequent failures and complications of the early synthetic ligaments. In China the LARS device was approved by the State Food and Drug Administration (SFDA) in 2004, and it has since been used on an ongoing basis. It has been estimated that more than 10,000 cases were performed. More than 100 papers on the results of LARS ACL reconstruction have been published in Chinese, with some studies also being published in English in international journals. Some of these studies are discussed in the following section.

31.7.1 Outcomes

In 2010, Gao et al. reported a multicenter study of 159 procedures performed in August 2004 and July 2006 [9]. The mean follow-up was 50 months. There were three graft ruptures, and one of these patients developed synovitis. Excessive anterior knee laxity was observed in another four cases, giving an overall failure rate being 4.4 %. Ninety-three percent of patients were satisfied with the outcome of their procedure.

In another midterm follow-up, a study by Liu et al. retrospectively compared LARS ACL reconstructions with four-strand hamstring autografts at a minimum of 4 years [16]. Anterior knee laxity was slightly but significantly greater in the hamstring group, but no other differences were seen between the two groups. The mean age of the patients at surgery was 33.9 years.

Pan et al. compared LARS and patellar tendon autograft ACL reconstructions in 62 patients at a minimum of 4 years [25]. No significant differences were seen between the two groups with respect to Lysholm, Tegner, and IKDC scores and anterior knee laxity. Once again, it should be noted that the mean age of patients at surgery was 34.9 years.

In a prospective randomized study, Chen et al. compared acute and delayed ACL reconstruction with a LARS device. Patients selected LARS their preferred graft before being enrolled in the study. Their mean age at surgery was 30.7 years. At 5 years, anterior knee laxity was decreased, and quadriceps muscle strength was increased in the acute group. There were no statistically significant differences in Lysholm, Tegner, or IKDC scores between the two groups.

In a longer-term follow-up, Wang et al. reported on a group of 38 patients who underwent ACL reconstruction with a LARS device. Twenty-eight patients were available for review at a minimum of 8 years (mean 11.4 years). The mean age at surgery was 36.1 years. There were six failures (21.4 %) due to graft rupture (two) or laxity (four). There was a significant improvement in the Lysholm and Tegner scores compared to preoperatively.

As with the general literature, the reported results of the LARS for ACL reconstruction show considerable variability. It is noteworthy that the average age of the patients in these is often older than typically reported in studies of ACL reconstruction. This may imply a reduced physical demand and therefore a likelihood of satisfaction with a degree of laxity that might not be tolerated in a younger and more active patient population.

31.8 Future Directions

The fundamental requirements of a synthetic ligament include (1) appropriate mechanical properties (high tensile strength, elasticity in keeping with the native ACL, and fatigue resistance), (2) biocompatibility including being hydrophilic and fostering fibrous ingrowth, (3) osteoconductive and osteoinductive capability to achieve better graft-bone healing, and (4) appropriate fixation methods.

To this end some of the areas of current and future research are listed below.

31.8.1 Improvements of Materials

Various coatings have been applied to the intra-articular and extra-articular portions of PET ligaments to encourage fibrous and bony ingrowth, respectively. Animal models using a coating of the intra-articular fibers with fibroin, the core protein of silk, have been encouraging [37]. Various coatings of the extra-articular component, including bioglass, hydroxyapatite, and silicon dioxide, have also been shown to improve osseointegration, again in animal models [38, 39].

Other non-resorbable materials such as nitinol, carbon nanotubes, and ultrahigh molecular-weight polyethylene are also being investigated as alternatives to PET.

An alternative strategy is to use other materials to create a biodegradable scaffold. Regenerated silk is one such material that has shown improved osteoinductivity and osteoconductivity of mesenchymal stem cells [40].

31.8.2 Alternative Fixation Methods

The LARS ligament was initially fixed with interference screws at both ends. However, these may reduce the porous nature of the ligament and thereby inhibit tissue ingrowth. Alternative fixation methods such as suspensory fixation may offer adequate fixation but at the same time allow for tissue ingrowth.

31.8.3 Optimization of Surgical Technique

As with all types of ACL reconstruction, a better understanding of the ideal bone tunnel locations and a precise and reproducible method for identifying these locations intraoperatively are likely to lead to improved outcomes.

Conclusion

While most synthetic grafts for ACL reconstruction have been abandoned, one device (LARS) continues to be used, particularly in China. The reported results are variable, but it has been associated with good outcomes in patients aged over 30 years. Synovitis appears to be less of a problem than with earlier synthetic grafts. Further research is required to delineate the role of synthetic ligaments in ACL reconstruction, and the use of alternative materials, other fixation methods, and biological coatings may all improve outcomes.

References

1. Barrett GR, Line LJ, Shelton WR, Manning JO, Phelps R (1993) The Dacron ligament prosthesis in anterior cruciate ligament reconstruction. A four-year review. Am J Sports Med 21(3):367–373
2. Bartolozzi P, Salvi M, Velluti C (1990) Long-term follow-up of 53 cases of chronic lesion of the anterior cruciate ligament treated with an artificial Dacron Stryker ligament. Ital J Orthop Traumatol 16(4):467–480
3. Batty LM, Norsworthy CJ, Lash NJ, Wasiak J, Richmond AK, Feller JA (2015) Synthetic devices for reconstructive surgery of the cruciate ligaments:

a systematic review. Arthroscopy 31(5):957–968. doi:10.1016/j.arthro.2014.11.032

4. Chen J, Gu A, Jiang H, Zhang W, Yu X (2015) A comparison of acute and chronic anterior cruciate ligament reconstruction using LARS artificial ligaments: a randomized prospective study with a 5-year follow-up. Arch Orthop Trauma Surg 135(1):95–102. doi:10.1007/s00402-014-2108-3
5. Claes L, Neugebauer R (1985) In vivo and in vitro investigation of the long-term behavior and fatigue strength of carbon fiber ligament replacement. Clin Orthop Relat Res 196:99–111
6. Dahlstedt L, Dalen N, Jonsson U (1990) Goretex prosthetic ligament vs. Kennedy ligament augmentation device in anterior cruciate ligament reconstruction. A prospective randomized 3-year follow-up of 41 cases. Acta Orthop Scand 61(3):217–224
7. Drogset JO, Grontvedt T, Robak OR, Molster A, Viset AT, Engebretsen L (2006) A sixteen-year follow-up of three operative techniques for the treatment of acute ruptures of the anterior cruciate ligament. J Bone Joint Surg 88(5):944–952. doi:10.2106/JBJS.D.02876
8. Foster IW, Ralis ZA, McKibbin B, Jenkins DH (1978) Biological reaction to carbon fiber implants: the formation and structure of a carbon-induced “neotendon”. Clin Orthop Relat Res 131:299–307
9. Gao K, Chen S, Wang L, Zhang W, Kang Y, Dong Q, Zhou H, Li L (2010) Anterior cruciate ligament reconstruction with LARS artificial ligament: a multicenter study with 3- to 5-year follow-up. Arthrosc: J Arthrosc Relat Surg 26(4):515–523. doi:10.1016/j.arthro.2010.02.001
10. Glezos CM, Waller A, Bourke HE, Salmon LJ, Pinczewski LA (2012) Disabling synovitis associated with LARS artificial ligament use in anterior cruciate ligament reconstruction: a case report. Am J Sports Med 40(5):1167–1171. doi:10.1177/0363546512438510
11. Grontvedt T, Engebretsen L (1995) Comparison between two techniques for surgical repair of the acutely torn anterior cruciate ligament. A prospective, randomized follow-up study of 48 patients. Scand J Med Sci Sports 5(6):358–363
12. Hamido F, Misfer AK, Al Harran H, Khadrawe TA, Soliman A, Talaat A, Awad A, Khairat S (2011) The use of the LARS artificial ligament to augment a short or undersized ACL hamstrings tendon graft. Knee 18(6):373–378. doi:10.1016/j.knee.2010.09.003
13. Jenkins DH (1978) The repair of cruciate ligaments with flexible carbon fibre. A longer term study of the induction of new ligaments and of the fate of the implanted carbon. J Bone Joint Surg Br 60-B(4):520–522
14. Jenkins DH, Forster IW, McKibbin B, Ralis ZA (1977) Induction of tendon and ligament formation by carbon implants. J Bone Joint Surg (Br) 59(1):53–57
15. Jenkins DH, McKibbin B (1980) The role of flexible carbon-fibre implants as tendon and ligament substitutes in clinical practice. A preliminary report. J Bone Joint Surg (Br) 62-B(4):497–499
16. Liu ZT, Zhang XL, Jiang Y, Zeng BF (2010) Four-strand hamstring tendon autograft versus LARS artificial ligament for anterior cruciate ligament reconstruction. Int Orthop 34(1):45–49. doi:10.1007/s00264-009-0768-3
17. Macnicol MF, Penny ID, Sheppard L (1991) Early results of the Leeds-Keio anterior cruciate ligament replacement. J Bone Joint Surg (Br) 73(3):377–380
18. Makisalo SE, Visuri T, Viljanen A, Jokio P (1996) Reconstruction of the anterior cruciate ligament with carbon fibres: unsatisfactory results after 8 years. Knee Surg Sports Traumatol Arthrosc 4(3):132–136
19. Maletius W, Gillquist J (1997) Long-term results of anterior cruciate ligament reconstruction with a Dacron prosthesis. The frequency of osteoarthritis after seven to eleven years. Am J Sports Med 25(3):288–293
20. Markolf KL, Pattee GA, Strum GM, Gallick GS, Sherman OH, Nuys V, Dorey FJ (1989) Instrumented measurements of laxity in patients who have a Gore-Tex anterior cruciate-ligament substitute. J Bone Joint Surg 71(6):887–893
21. Moyen BJ, Jenny JY, Mandrino AH, Lerat JL (1992) Comparison of reconstruction of the anterior cruciate ligament with and without a Kennedy ligament-augmentation device. A randomized, prospective study. J Bone Joint Surg Am 74(9):1313–1319
22. Mulford JS, Chen D (2011) Anterior cruciate ligament reconstruction: a systematic review of polyethylene terephthalate grafts. ANZ J Surg 81(11):785–789
23. Murray AW, Macnicol MF (2004) 10–16 year results of Leeds-Keio anterior cruciate ligament reconstruction. Knee 11(1):9–14. doi:10.1016/S0968-0160(03)00076-0
24. Newman SD, Atkinson HD, Willis-Owen CA (2013) Anterior cruciate ligament reconstruction with the ligament augmentation and reconstruction system: a systematic review. Int Orthop 37(2):321–-326. doi:10.1007/s00264-012-1654-y
25. Pan X, Wen H, Wang L, Ge T (2013) Bone-patellar tendon-bone autograft versus LARS artificial ligament for anterior cruciate ligament reconstruction. Eur J Orthop Surg Traumatol 23(7):819–823. doi:10.1007/s00590-012-1073-1
26. Parchi PD, Gianluca C, Dolfi L, Baluganti A, Nicola P, Chiellini F, Lisanti M (2013) Anterior cruciate ligament reconstruction with LARS™ artificial ligament results at a mean follow-up of eight years. Int Orthop 37(8):1567–1574. doi:10.1007/s00264-013-1917-2
27. Paulos LE, Rosenberg TD, Grewe SR, Tearse DS, Beck CL (1992) The GORE-TEX anterior cruciate ligament prosthesis. A long-term follow up. Am J Sports Med 20(3):246–252

28. Glousman R, Shields C, Kerlan R, Jobe F (1988) Gore-Tex prosthetic ligament in anterior cruciate deficient knees. Am J Sports Med 16(4):321–326. doi:10.1177/036354658801600402
29. Roth JH, Shkrum MJ, Bray RC (1988) Synovial reaction associated with disruption of polypropylene braid-augmented intraarticular anterior cruciate ligament reconstruction. A case report. Am J Sports Med 16(3):301–305
30. Schroven IT, Geens S, Beckers L, Lagrange W, Fabry G (1994) Experience with the Leeds-Keio artificial ligament for anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 2(4):214–218. doi:10.1007/BF01845590
31. Struewer J, Ziring E, Ishaque B, Efe T, Schwarting T, Buecking B, Schuttler KF, Ruchholtz S, Frangen TM (2013) Second-look arthroscopic findings and clinical results after polyethylene terephthalate augmented anterior cruciate ligament reconstruction. Int Orthop 37(2):327–335. doi:10.1007/s00264-012-1652-0
32. Tayton K, Phillips G, Ralis Z (1982) Long-term effects of carbon fibre on soft tissues. J Bone Joint Surg (Br) 64(1):112–114
33. Tiefenboeck TM, Thurmaier E, Tiefenboeck MM, Ostermann RC, Joestl J, Winnisch M, Schurz M, Hajdu S, Hofbauer M (2015) Clinical and functional outcome after anterior cruciate ligament reconstruction using the LARS system at a minimum follow-up of 10 years. Knee. doi:10.1016/j.knee.2015.06.003
34. Ventura A, Legnani C, Terzaghi C, Borgo E, Albisetti W (2014) Revision surgery after failed ACL reconstruction with artificial ligaments: clinical, histologic and radiographic evaluation. Eur J Orthop Surg Traumatol 24(1):93–98. doi:10.1007/s00590-012-1136-3
35. Wang C, Hsiao C, Ku M, Chang C (2013) Arthroscopic anterior cruciate ligament reconstruction with LARS artificial ligament: an 8–15-year follow-up. J Mech Med Biol 13(02). doi:10.1142/S0219519413500462
36. Woods GA, Indelicato PA, Prevot TJ (1991) The Gore-Tex anterior cruciate ligament prosthesis. Two versus three year results. Am J Sports Med 19(1):48–55
37. Jiang J, Hao W, Li Y, Yao J, Shao Z, Li H et al (2013) Hydroxyapatite/regenerated silk fibroin scaffold-enhanced osteoinductivity and osteoconductivity of bone marrow-derived mesenchymal stromal cells. Biotechnol Lett 35(4):657–661. doi:10.1007/s10529-012-1121-2
38. Li H, Yang W, Ge Y, Jiang J, Gao K, Zhang P et al (2011) Composite coating of 58S bioglass and hydroxyapatite on a poly (ethylene terephthalate) artificial ligament graft for the graft osseointegration in a bone tunnel. Appl Surf Sci 257(22):9371–9376
39. Cho S, Li H, Chen C, Jiang J, Tao H, Chen S (2013) Cationised gelatin and hyaluronic acid coating enhances polyethylene terephthalate artificial ligament graft osseointegration in porcine bone tunnels. Int Orthop 37(3):507–513. doi:10.1007/s00264-012-1694-3
40. Jiang J, Ai C, Zhan Z, Zhang P, Wan F, Chen J et al (2015) Enhanced fibroblast cellular ligamentization process to polyethylene terephthalate artificial ligament by silk fibroin coating. Artif Organs. doi:10.1111/aor.12571

Xenograft Ligaments

32

Kevin R. Stone and Uri Galili

32.1 Introduction

Effective off-the-shelf natural ligament devices for cruciate ligament reconstruction represent the ideal solution to the problem of ligament rupture. This chapter will focus on xenograft tissues as they represent the possibility of a natural tissue graft which can be sourced from a young healthy source and remodel into the recipient's own tissue. The basic science and clinical trials of the first successful xenograft ligament device will be discussed.

32.2 Background: Why an Off-the-Shelf Ligament?

The anterior cruciate ligament (ACL) is the key stabilizer of the knee joint and is frequently injured in athletic activities. Over 350,000 patients with damaged ACLs undergo inpatient or outpatient surgical intervention in the USA each year [38]. Current surgical techniques consist of either the use of the patient's own tissue to reconstruct the ACL (autologous harvest procedures) or, less frequently, cadaveric tissue grafts (allografts). Grafts used to reconstruct the ACL include constructs of the bone-tendon-bone, bone-tendon, and soft tissue tendon. All grafting techniques have disadvantages and risks. Reconstruction utilizing an autologous harvest procedure involves two surgical sites, the primary operative site and the additional harvest site. The harvest procedure for reconstruction often results in larger or additional incisions, increased pain, longer recovery periods, and increased morbidity [5, 16, 17]. Adverse effects from the harvest procedure may include patellar fracture, patellar tendon rupture with scar formation, and muscle weakness [2, 22, 35]. Cadaveric tissue allografts offer a limited source of ACL replacement tissue due to the scarcity of available tissue from young healthy donors. Variability in tissue quality and performance is also an issue between donors. The risk of transmission of adventitious disease has been another obstacle to the acceptance of cadaveric tissue [25].

Clinical ACL reconstruction (ACLR) with synthetic and nonhuman tissue-based devices has led to failure due to a range of factors including material property mismatch, fatigue, abrasion, particulate shedding, poor fixation, anatomical placement, and immunological rejection [6, 10, 19, 29, 36]. The cause of immunological rejection when transplanting animal tissues into humans was identified in multiple studies as a reaction to the carbohydrate

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antigen called "α-Gal epitope" present in high concentration on animal tissues but completely absent in humans [1, 13, 32, 37]. In contrast, humans, apes, and old-world monkeys (monkeys of Asia and Africa) produce large amounts of a natural antibody called "anti-Gal" that binds effectively to α-gal epitopes [14]. Stone and coworkers demonstrated the utility of treating porcine tissues with the glycosidase enzyme, α-galactosidase, effectively attenuating graft-to-host immune recognition by α-Gal epitope cleavage [3, 13, 24, 31]. The objective of these investigations was to develop an immunocompatible, dynamic bioimplant xenograft for ACL reconstruction with characteristics matching homologous human tissue.

32.3 Creation of a Chronic Xenograft Rejection Model

Transplantation of discordant xenograft organs such as the heart or kidney into monkeys results in a hyperacute antibody-mediated rejection response and likely due to the anti-Gal-mediated destruction of endothelial cells and collapse of the vascular bed. The resulting graft destruction is evident within 30 min to a few days after implantation. Since cartilage has limited vascularity, there is less potential for hyperacute rejection. It had been speculated that articular cartilage might be immunoprivileged and therefore xenograft cartilage might be immunocompatible [20]. Xenograft porcine and bovine meniscal and articular cartilage tissues were transplanted into the suprapatellar pouches of nonhuman primates (old-world monkeys producing anti-Gal) for 1 or 2 months postoperatively [33]. The results suggested that xenograft cartilage tissue was not as immunocompatible as reported and was determined to be unsuitable for human implantation due to a chronic rejection mechanism which was evident within 1 month after transplantation. The rejection mechanism was due to the detrimental effects of the natural anti-Gal antibody and to the production of antibodies directed against non α-gal porcine antigens (porcine proteins that are immunogenic in primates, called anti-non-Gal antibodies). Histologically, the rejection response was characterized by a strong cellular inflammatory response of T lymphocytes and macrophages within the implants. Clearly, xenografts would need to be modified in order to decrease or eliminate the robust rejection response that results in premature graft destruction.

32.4 Changes in Anti-Gal Response During Chronic Rejection

Following the development of the xenograft rejection model [33], Galili et al. published a study of the characteristics of the immune response in cynomolgus monkeys implanted with porcine or bovine cartilage for up to 2 months [13]. The study found that within 2 weeks after transplantation, the anti-Gal IgG titer in all implanted primates increased by 20–100 times at the baseline preimplantation serum level. Complement-mediated cytotoxicity also increased by two to eight times after transplantation. This elevated activity of anti-Gal was maintained for the 2-month period during which the grafts were kept in the primates and returned to the preimplantation level 6 months after graft removal. Previous studies in humans reported that about 1 % of B cells in humans are capable of producing the anti-Gal antibody; however, most of these B cells, referred to as anti-Gal B cells, are quiescent, and only those along the gastrointestinal tract produce the antibody [12]. The increase in anti-Gal titers in cynomolgus monkeys implied that the α-gal epitopes released from porcine xenografts induce rapid activation of anti-Gal B cells, resulting in marked elevation in anti-Gal titers. Galili et al. concluded that the elicited anti-Gal will further exacerbate the immune rejection of xenografts in primate recipients and directed further research efforts to developing a reliable method for elimination of the α-gal epitope from orthopedic porcine xenografts.

32.5 Implantation of α-Gal-Deficient Porcine Cartilage

Stone et al. studied the possible elimination of α-gal epitopes from xenograft cartilage by the use of recombinant α-galactosidase [31]. This enzyme cleaves terminal galactosyl unit from the α-gal epitope (Gal α1-3Galβ1-4GlcNAc-R) into the carbohydrate structure Galβ1-4GlcNAc-R which is also present on human cells and cannot bind the anti-Gal antibody. Porcine meniscus and articular cartilage specimens treated for 12 h with recombinant α-galactosidase were confirmed to completely lack this epitope. This was demonstrated by the inability of a monoclonal anti-Gal antibody to bind to these treated specimens in comparison to the extensive binding of the antibody to untreated specimens. The α-galactosidase-treated cartilage specimens were implanted into the suprapatellar pouch of cynomolgus monkeys, and the immune response to cartilage was monitored by serum evaluation and histology 2 months post-implantation.

The results of this study demonstrated no significant increase in anti-Gal activity after enzymatic elimination of α-gal epitopes from the treated grafts. The inflammatory response within the α-galactosidase-treated xenografts was lower by ~95 % than that in untreated cartilage, and the proportion of T lymphocytes within the cellular infiltrates was greatly reduced [31]. However, the removal of α-gal epitopes did not eliminate the immune response to non-Gal antigens. Most monkeys produced anti-non-Gal antibodies to non-Gal antigens in porcine cartilage. The reason for this anti-non-Gal antibody response is that most porcine proteins differ from homologous proteins in monkeys (as well as in humans); therefore, they elicit antibody response against differences. The production of anti-non-Gal antibodies resulted in induction of a reduced inflammatory response consisting primarily of macrophages infiltrating into the cartilage. These macrophages bind via their Fc receptors to anti-non-Gal antibodies immunocomplexed with the immunogenic porcine cartilage proteins and are likely to cause destruction of the xenograft, albeit at a pace that is much slower than the destruction in the presence of α-gal epitopes. The anti-non-Gal-mediated destruction of orthopedic xenografts led to developing methods to attenuate this immune response, increasing the clinical utility for using xenograft devices.

32.6 Development of a Xenograft for ACL Reconstruction

32.6.1 Immunological and Biomaterial Considerations

Several strategies have been used for transplantation into humans of devices prepared from animal tissues. Below are models describing strategies for the following devices and tissue types: (i) vascular grafts and heart valves and (ii) soft tissue augmentation devices. These models were used to create an understanding of the design constraints for xenograft device development and clinical performance.

Porcine Heart Valves and Vascular Graft Vascular bioprosthetics are heavily processed to eliminate any live cells in the tissue and to blunt any immunological response to the implant. The processing required also renders the implant virtually inert, with little to no cellular ingrowth into the device. The implanted device is subject to cumulative wear and fatigue similar to artificial material-manufactured devices. Porcine-derived heart valve prostheses exemplify this approach to the use of animal tissue for functional reconstruction [8, 15]. Porcine heart valves are treated with high levels of glutaraldehyde for extended periods, rendering a device which is highly cross-linked. The glutaraldehyde treatment blocks host cellular repopulation and proliferation but does not completely alleviate peripheral immunological recognition [18]. The potential for a lifetime duty cycle of the device is limited by a combination of cumulative mechanical fatigue, surface defect propagation, and subsequent calcification. These constraints make a bioprosthetic valve suitable for older patients, but not generally suitable for younger, more immunologically active. Figure 32.1 proposes a model for processing and long-term host response to a porcine vascular tissue.

Soft Tissue Augmentation Devices Recent developments in orthopedic soft tissue reconstruction have involved the development of xenograft tissue augmentation devices. These materials

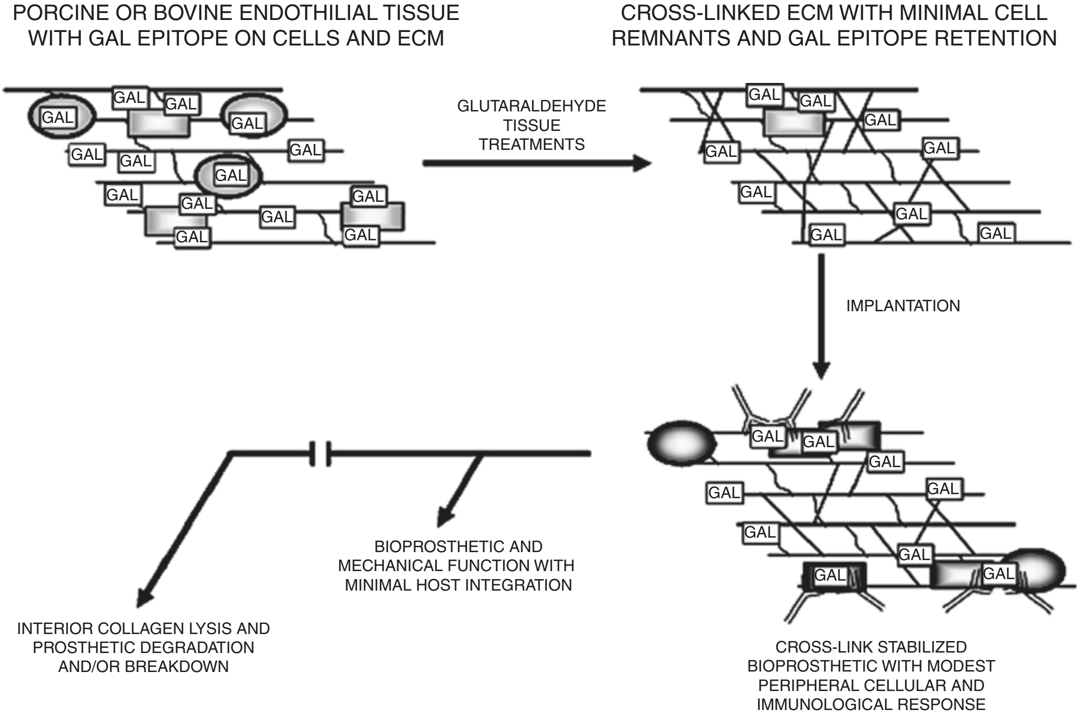

Fig. 32.1 Bioprosthetic glutaraldehyde-treated vascular grafts

are subjected to a rigorous washing process that strips the tissue of many cellular components; however, the process does not remove α-Gal epitopes. They are designed to augment existing structures and are subsequently replaced by host tissue in a relatively short time frame. Upon implantation, the device elicits a robust foreign body reaction, both to the α-Gal epitope and other proteins, resulting in an inflammatory process and replacement with fibrotic (scar) tissue that does not replicated the normal tissue [1, 23]. The clinical utility of the device is limited by the short residence time of the material mediated by inflammation and rapid post-implantation decline in device mechanical integrity. Figure 32.2 illustrates soft tissue augmentation device treatment and host response.

More current treatments with α-galactosidase enzyme are used permanently to remove α-Gal from porcine connective tissues. Studies in primates showed a >95 % reduction in immunological response through removal of the α-Gal epitope [13, 31]. Enzymatic elimination of the α-Gal epitope is not effective in the living organs frequently studied for transplantation due to the continual synthesis of the epitope by transplanted cells. However, since treated devices do not contain any live cells, the enzymatic depletion of α-Gal epitopes is permanent.

There are many secondary epitopes that elicit a low-level immune response. The immune-mediated destruction of the devices depleted of α-Gal epitopes is further minimized by treatment including glutaraldehyde cross-linking followed by end-capping, freezing, and irradiation. Because primary host immunological response has been attenuated by the use of the enzymatic treatment, we were able to use significantly lower glutaraldehyde treatment levels than those used in other devices.

The devices that result from this combination of treatments are very different from traditional static bioprosthetics. The reduced processing provides a device that is more biocompatible and biomechanically superior. Most importantly, the low-level treatments do not block migration

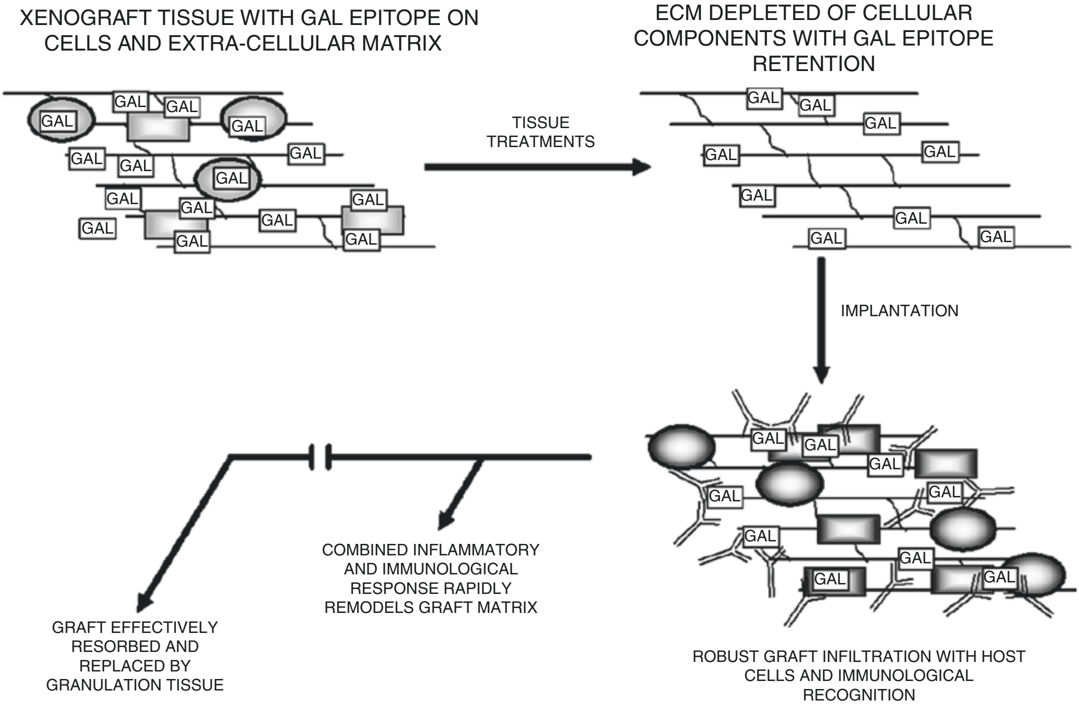

Fig. 32.2 Soft tissue augmentation devices

of host cells into the device, gradually replacing the implanted device with a new tissue. Thus, as described below, macrophages can penetrate the device, albeit at a slow enough pace that enables the remodeling by host cells (e.g., blood vessels and fibroblasts) that infiltrate via the pathways formed by these macrophages. Reestablishment of original tissue morphology is a tremendous advantage since the patient's own body repairs the graft from cumulative wear. Immunochemically modified tissue-derived devices provide biomechanical support and functionality to the patient immediately upon implantation and throughout the period of regrowth of the patients' own tissue (ligamentization) [11, 21].

32.6.2 Xenograft Processing Overview

Based on the considerations above, a focused effort was undertaken to develop a xenograft ligament device from a section of the porcine patellar tendon with bone blocks and based on the immunogenicity mechanisms learned from the previous series of primate studies. Grafts were sourced from a porcine stifle and processed into a bone-tendon-bone (BTB) configuration. The graft was exposed to a series of chemical treatments. First, decellularization treatment to remove intact porcine cells and cellular components, followed by exposure to recombinant α-galactosidase enzyme solution to cleave α-gal epitopes from the graft. Removal of these α-gal epitopes was confirmed by ELISA testing with a monoclonal anti-Gal antibody that demonstrated that essentially 100 % of these epitopes were removed from the tendon portion of the construct. Following enzyme treatment, low-level glutaraldehyde cross-linking treatment was employed, with the intention of attenuating the anti-non-Gal-mediated destruction by the host immune system. We determined empirically incubating tendons in low-level glutaraldehyde followed by glycine quench of aldehyde yields for optimal conditions for macrophage infiltration allowing for the gradual remodeling of implants.

Table 32.1 Structural properties of biomechanical tensile test groups

	Porcine patellar tendon treated (pPT) ($n = 10$)	Human patellar tendon (hPT) ($n = 10$)	Human ACL (16–26 years) ($n = 6$) [26]	Human ACL (48–86 years) ($n = 20$) [26]
Ultimate load (N)	1,889 ± 252	1,387 ± 299	1,730 ± 660	734 ± 266
Yield load (N)	1,437 ± 256	1,101 ± 397	1,170 ± 750	622 ± 283
Ultimate displacement (mm)	20.5 ± 5.5	15.1 ± 4.5	11.8	8.3
Yield displacement (mm)	14.0 ± 4.3	11.7 ± 3.6	6.9	6.0
Stiffness (N/mm)	184.2 ± 34.8	181.9 ± 79.5	182 ± 56	129 ± 39

The final stage of treatment included packaging and exposure of the hydrated graft to 17.8 kGy of e-beam irradiation, a low level of irradiation intended to provide graft sterility while minimizing the degradative effects of radiation.

32.6.3 Biomechanical Evaluation

In order to mechanically characterize treated and sterilized porcine grafts, we used clinically relevant controls for comparative biomechanical evaluations and used standardized static testing methods. The two test groups included treated porcine device (pPT) and human bone-patellar tendon-bone allograft (hPT) cut to 9-mm width. Ten grafts were used in each assessment group. All testing used fresh-frozen grafts stored frozen and thawed just before testing. Porcine ligament graft specimens were immunochemically processed, while human patellar tendon grafts were sourced from accredited tissue banks as humans use graded specimens.

Structural properties were determined from load displacement curves: ultimate load, yield load, ultimate displacement, yield displacement, and axial stiffness. Axial stiffness was calculated from linear slope. Conversion of these tensile properties was accomplished by normalization of stress vs. strain plots and specimen cross-sectional area. Structural and material properties were derived for all specimens. A retrospective comparison of our porcine and human patellar tendon results from Noyes 1976 study evaluating young and old human anterior cruciate ligaments is shown for physical, structural, and material properties [27]. The biomechanical characterization of the specimens compared processed xenograft with human allograft. Human ACL construct groups are presented from Noyes 1976 study. Cross-sectional area and bone-to-bone length of the tested graft groups closely approximate the ACL. The structural properties of ultimate load, yield load, ultimate displacement, yield displacement, and stiffness in ten grafts are presented in Table 32.1.

No significant differences were found between xenograft device and human patellar tendon test groups in the structural parameters of yield load, ultimate displacement, yield displacement, stiffness, or yield strength. No significant differences were found between these test groups in the material parameters of ultimate strain, yield strain, or modulus. The xenograft device exhibited significantly greater ultimate load, ultimate strength, and yield strength as compared to human patellar tendon grafts. Xenograft device material property results compare favorably to ACLs of young donors as reported in the literature and resulted in an activity force limit 1.3 times the ultimate strength of young donor ACLs [26].

32.6.4 Primate Anterior Cruciate Ligament Reconstruction

An ACL reconstruction study in primates was performed in 20 rhesus monkeys to evaluate the feasibility of the graft as an ACL reconstruction graft [34]. Testing involved a unilateral primate ACL reconstruction model with 2-, 6-, and 12-month sacrifice time points and clinical, histological, and biomechanical assessments. Control groups included primates implanted with an unprocessed porcine graft and allograft-implanted primates. Evaluation methods included

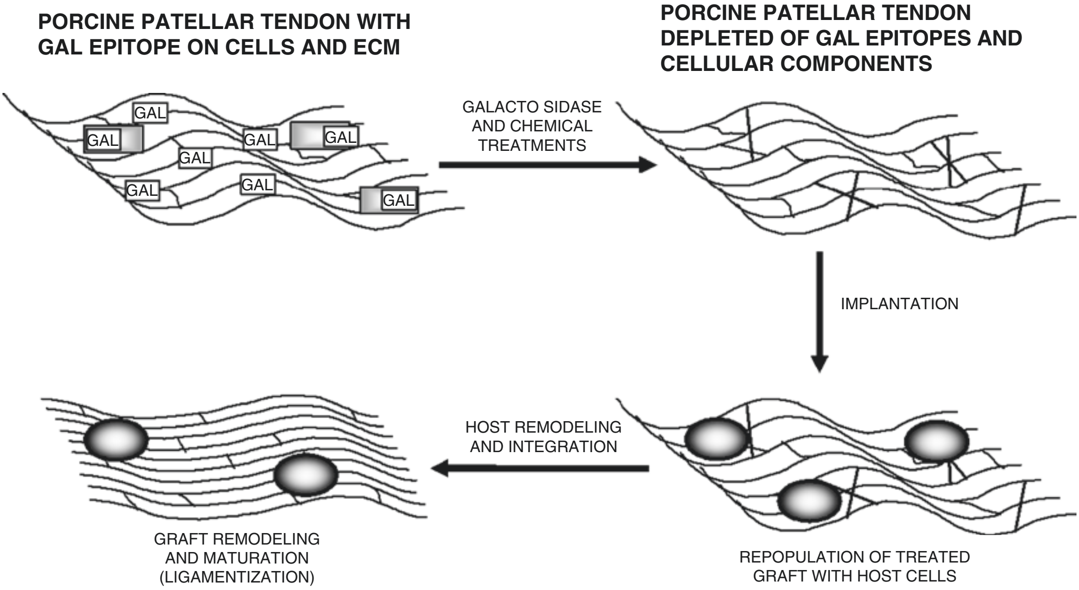

Fig. 32.3 Treated porcine ACL reconstruction device

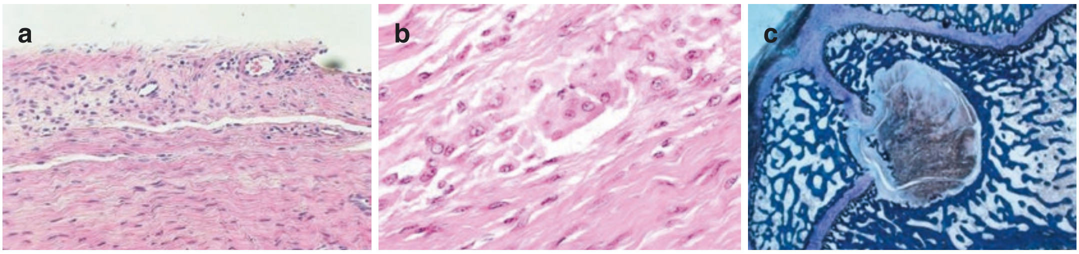

Fig. 32.4 (**a**–**c**) Rhesus allograft histology, 2 months. (**a**) Intra-articular portion of the graft showing peripheral synovial formation and collagen fiber alignment (H&E, 10×). (**b**) Fibroblastic reorganization of graft with modest fibrohistiocytic infiltration (H&E, 40×). (**c**) Femoral bone tunnel showing graft integration and host bone remodeling (toluidine blue, 10×)

objective functional assessment in life, radiology, serological testing of anti-Gal and anti-non-Gal antibody response, and clinical and serum chemistry. Post-sacrifice assessments included gross pathology, organ histopathology, implant histology, and postmortem biomechanics. All animals returned to normal function by 7 weeks postoperatively. Range of motion and laxity were assessed at 6 and 12 months by manual manipulation and comparison to contralateral, unoperated limbs. All range of motion and laxity measurements were considered to be clinically acceptable considering the surgical and anatomical complexities of the small primate knee. No clinically significant differences between allograft and treated porcine grafts were noted in either clinical end point. Two-month histology presented in Figs. 32.3, 32.4, 32.5, and 32.6 demonstrated parallel development between rhesus autograft and treated porcine groups in contrast to frank rejection in the untreated porcine group.

Postmortem ex vivo biomechanical properties of the ligamentized treated xenograft after 6 and 12 months were not significantly different compared to the primate allograft cohort and compared favorably with various published values for autograft reconstructions in animals. The ligamentized treated xenograft either equaled or

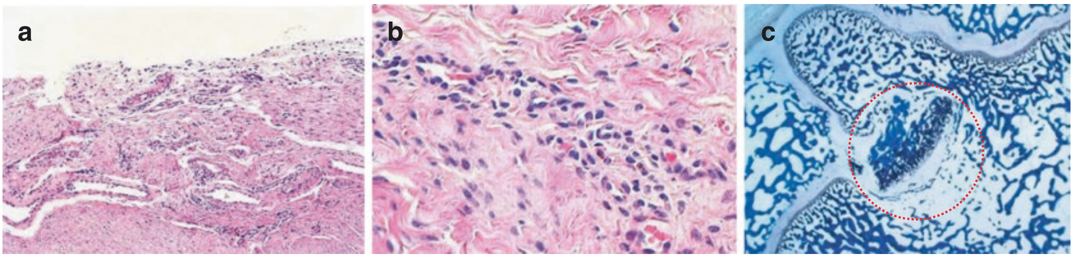

Fig. 32.5 (**a**–**c**) Untreated porcine patellar tendon histology, 2 months. (**a**) Granular organization of the native intra-articular graft periphery without residual identifiable porcine elements (H&E, 20×). (**b**) Cellular infiltrate of lymphocytic cells (H&E, 20×). (**c**) Femoral bone tunnel showing considerable graft resorption by numerous giant cells and plasma cells with original tunnel margins indicated by the *dotted red line* (toluidine blue, 10×)

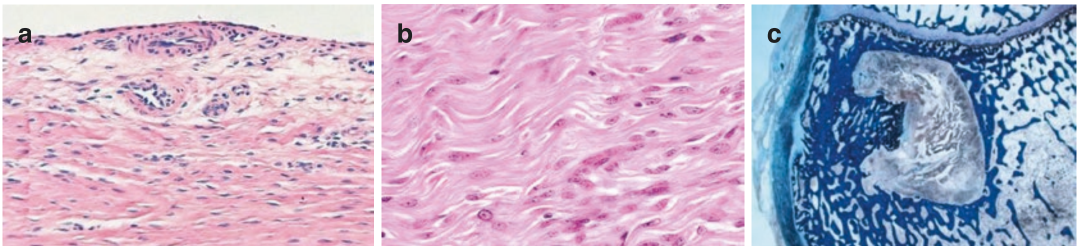

Fig. 32.6 (**a**–**c**) Xenograft device histology, 2 months. (**a**) Peripheral synovial formation and fibrovascular organization of the graft (H&E, 20×). (**b**) Fibroblastic remodeling in alignment with the collagen fibrils (H&E, 40×). (**c**) Femoral bone tunnel showing graft-to-host bone integration and new bone formation around the edge of the tunnel (toluidine blue, 10×)

exceeded the published strength of these autograft reconstructions performed in various animal models including primates [4, 7, 9, 28].

32.7 Human Clinical Evaluation: The US Pilot Study

Based on the preclinical studies in primates, an FDA-approved single-center feasibility clinical study of the treated xenograft was performed in ten subjects, all of whom received the treated xenograft [30]. Primary study end points were knee stability and effusion. Secondary end points of the study involved study participants who rated subjective evaluations through specific standardized reporting tools. In addition, each patient's radiograph and MRI were assessed by an independent musculoskeletal radiologist; blood chemistry, urine chemistry, and serum antibody levels were studied at various time points throughout the study. Of six evaluable subjects, five presented with functional grafts at the 24-month postoperative time point and satisfied all study success criteria including effusion, KT-1000, pivot shift, and Lachman and Anterior Drawer tests. The remaining subject presented with tibial bone plug loosening at 15 months post ACL reconstruction and had his xenograft removed and tibial tunnel grafted with cancellous allograft. Four subjects were non-evaluable due to non-device-related complications during the study due to trauma and very early return to sports. There was only one serious adverse event (SAE) that was determined to be graft related. The other four SAEs were reported in the four non-evaluable subjects, each of whom experienced a non-graft-related SAE during the study. The anti-Gal IgG antibody response corresponding to α-gal epitope recognition elevated postoperatively to a low peak at 2 months and then decreased to preimplant range over the period from 2 to 12 months. Anti-non-Gal response peaked at approximately 6 months and resolved to preimplant range by 24 months suggesting that most of the porcine tissue in the subjects had been replaced by the host and that the implant had regenerated into a de novo ACL while maintaining all that time its structural integrity.

Porcine tendon implants explanted by secondary surgical interventions from five of the patients, due primarily to sports injuries, provided a better understanding of the ligamentization process. Prior to implantation, the processed porcine tendon contains primarily the collagen fiber bioscaffold and the associated matrix proteins. Anti-non-Gal antibodies are likely to contribute to the observed infiltration of macrophages into the transplanted porcine tendon. These infiltrating macrophages secrete cytokines, including VEGF, that induce vascularization of the implant. The recipient's fibroblasts infiltrate the implant via newly formed blood vessels and align with the collagen fiber scaffold. These fibroblasts secrete their own collagen fibers and thus convert the implanted tendon into a viable ACL.

None of the histology indicated significant inflammatory, immunological, or other destructive rejection response, other than normal ligamentization process. The cell populations of biopsies were consistent with expected phases of healing and supported host cell-mediated remodeling of the xenograft. Synovial biopsies exhibited no signs of synovitis. Blood chemistry, urine chemistry, and serology results were within normal ranges at the 24-month time point.

MRI results in all five patients with xenograft reconstructions indicated contiguous reconstructions with maturing graft and normalizing signal intensity. The variability observed in the healing, the technical errors, and the early traumatic ruptures of these xenografts were similar to the clinical experience with allografts and the experience reported in the literature. At 12-year follow-up each of the five evaluable patients continued to participate in sports with stable knees. This safety study tested the xenograft in a niche subject population, as a worst-case scenario, including those with high Tegner activity scores (average score of 7.4, competitive sports level), who were aggressive in rehabilitation and rapidly returned to full sports participation early in the postoperative period. Moreover, enrolled subjects included those with clinically significant concomitant injuries as well as those who were undergoing revision surgeries; these are well-known risks to outcomes following ACL reconstruction. In summary, the xenografts were well tolerated without observation of a negative immunogenic response. In five of six evaluable subjects, the xenograft satisfied functional stability assessments and continue to function in the most recent 12-year follow-up evaluations.

The study feasibility objectives of surgical implantability, safety, and preliminary efficacy were demonstrated. The FDA subsequently approved an Investigational Device Exemption (IDE) allowing xenograft evaluation in a multicenter pivotal trial in the USA.

32.8 Further Research

Following the completion of the pilot clinical trial described above, a pivotal study clinical study was conducted in seven centers in the European Union and South Africa. This clinical study is an ongoing evaluation of the long-term safety and performance of the xenograft for the treatment of ruptured ACL of the knee compared to allograft. The trial was designed as a prospective, randomized, double-blind, multicenter noninferiority clinical trial in 66 subjects. Sixty-six patients with acute or chronic ACL ruptures undergoing ACL Reconstruction were randomized 1:1 to receive the xenograft or allograft device. At the time of writing, 24-month data has been collected on all patients, and the subsequent analysis is pending publication. A review of the data presented to the notified body led to a CE mark approval for sale of the xenograft ligament devices in CE mark countries. Future research into novel techniques for the removal of the non-Gal epitopes will likely improve device remodeling after implantation.

32.9 Summary

Basic science and clinical data appear to demonstrate efficacy of treated xenograft tissues in primates and a number of patients to date. The treatments strip the critical antigens and block the remaining antigens sufficiently to allow remodeling of the tissues. In the "do no harm" state of medicine, the development of off-the-shelf xenograft devices for ruptured cruciate ligaments as an alternative to both allografts and autografts is warranted. The immunogenicity reduction process may provide surgeons with a consistent supply of high-quality nonhuman tissue grafts.

References

1. Allman AJ, McPherson TB, Badylak SF et al (2001) Xenogeneic extracellular matrix grafts elicit a TH2-restricted immune response. Transplantation 71(11):1631–1640
2. Aufwerber S, Hagströmer M, Heijne A (2012) Donor-site-related functional problems following anterior cruciate ligament reconstruction: development of a self-administered questionnaire. Knee Surg Sports Traumatol Arthrosc 20(8):1611–1621
3. Badylak SF, Gilbert TW (2008) Immune response to biologic scaffold materials. Semin Immunol 20(2):109–116
4. Ballock RT, Woo SL, Lyon RM, Hollis JM, Akeson WH (1989) Use of patellar tendon autograft for anterior cruciate ligament reconstruction in the rabbit: a long-term histologic and biomechanical study. J Orthop Res 7(4):474–485
5. Bliddal H, Christensen R (2009) The treatment and prevention of knee osteoarthritis: a tool for clinical decision-making. Expert Opin Pharmacother 10(11):1793–1804
6. Bolton CW, Bruchman WC (1985) The GORE-TEX expanded polytetrafluoroethylene prosthetic ligament. An in vitro and in vivo evaluation. Clin Orthop Relat Res 196:202–213
7. Butler DL, Grood ES, Noyes FR et al (1989) Mechanical properties of primate vascularized vs. nonvascularized patellar tendon grafts; changes over time. J Orthop Res 7:68–79
8. Carpentier A, Lemaigre G, Robert L, Carpentier S, Dubost C (1969) Biological factors affecting long-term results of valvular heterografts. J Thorac Cardiovasc Surg 58(4):467–483
9. Clancy WG, Narechania RG, Rosenberg TD, Gmeiner JG, Wisnefske DD, Lange TA (1981) Anterior and posterior cruciate ligament reconstruction in rhesus monkeys. J Bone Joint Surg Am 63(8):1270–1284
10. Denti M, Bigoni M, Randelli P et al (1998) Graft-tunnel mismatch in endoscopic anterior cruciate ligament reconstruction. Intraoperative and cadaver measurement of the intra-articular graft length and the length of the patellar tendon. Knee Surg Sports Traumatol Arthrosc 6(3):165–168
11. Emmerson BC, Gortz S, Jamali AA, Chung C, Amiel D, Bugbee WD (2007) Fresh osteochondral allografting in the treatment of osteochondritis dissecans of the femoral condyle. Am J Sports Med 35(6):907–914
12. Galili U, Anaraki F, Thall A, Hill-Black C, Radic M (1993) One percent of human circulating B lymphocytes are capable of producing the natural anti-Gal antibody. Blood 82(8):2485–2493
13. Galili U, LaTemple DC, Walgenbach AW, Stone KR (1997) Porcine and bovine cartilage transplants in cynomolgus monkey: II. Changes in anti-Gal response during chronic rejection. Transplantation 63(5):646–651
14. Galili U (2013) Anti-Gal: an abundant human natural antibody of multiple pathogeneses and clinical benefits. Immunology 140(1):1–11
15. Haimov M, Jacobson JH (1974) Experience with the modified bovine arterial heterograft in peripheral vascular reconstruction and vascular access for hemodialysis. Ann Surg 180(3):291–295
16. Kartus J, Magnusson L, Stener S, Brandsson S, Eriksson BI, Karlsson J (1999) Complications following arthroscopic anterior cruciate ligament reconstruction. A 2–5-year follow-up of 604 patients with special emphasis on anterior knee pain. Knee Surg Sports Traumatol Arthrosc 7(1):2–8
17. Kohn D, Sander-Beuermann A (1994) Donor-site morbidity after harvest of a bone-tendon-bone patellar tendon autograft. Knee Surg Sports Traumatol Arthrosc 2(4):219–223
18. Konakci KZ, Bohle B, Blumer R et al (2005) Alpha-Gal on bioprostheses: xenograft immune response in cardiac surgery. Eur J Clin Invest 35(1):17–23
19. Lukianov AV, Richmond JC, Barrett GR, Gillquist J. A multicenter study on the results of anterior cruciate igament reconstruction using a dacron ligament prosthesis in "Salvage" cases. doi:10.1177/036354658901700312
20. Mankin HJ (1982) The response of articular cartilage to mechanical injury. J Bone Joint Surg Am 64(3):460–466
21. Marumo K, Saito M, Yamagishi T, Fujii K (2005) The "ligamentization" process in human anterior cruciate ligament reconstruction with autogenous patellar and hamstring tendons: a biochemical study. Am J Sports Med 33(8):1166–1173
22. Marumoto JM, Mitsunaga MM, Richardson AB, Medoff RJ, Mayfield GW (1996) Late patellar tendon ruptures after removal of the central third for anterior Cruciate ligament reconstruction. A report of two cases. Am J Sports Med 24:698–701
23. McPherson TB, Liang H, Record RD, Badylak SF (2000) Gal alpha(1,3)Gal epitope in porcine small intestinal submucosa. Tissue Eng 6(3):233–239
24. Naso F, Gandaglia A, Iop L, Spina M, Gerosa G (2012) Alpha-Gal detectors in xenotransplantation research: a word of caution. Xenotransplantation 19(4):215–220
25. Nemzek JA, Arnoczky SP, Swenson CL (1994) Retroviral transmission by the transplantation of connective-tissue allografts. An experimental study. J Bone Joint Surg Am 76(7):1036–1041

26. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS (1984) Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. J Bone Joint Surg Am 66(3):344–352
27. Noyes FR, Grood ES (1976) The strength of the anterior cruciate ligament in humans and rhesus monkeys. J Bone Joint Surg Am 58(8):1074–1082
28. Schindhelm K, Rogers GJ, Milthorpe BK et al (1991) Autograft and Leeds-Keio reconstructions of the ovine anterior cruciate ligament. Clin Orthop Relat Res 267:278–293
29. Van Steensel CJ, Schreuder O, van den Bosch BF et al (1987) Failure of anterior cruciate-ligament reconstruction using tendon xenograft. J Bone Joint Surg Am 69:860–864
30. Stone KR, Abdel-Motal UM, Walgenbach AW, Turek TJ, Galili U (2007) Replacement of human anterior cruciate ligaments with pig ligaments: a model for anti-non-gal antibody response in long-term xenotransplantation. Transplantation 83(2):211–219
31. Stone KR, Ayala G, Goldstein J, Hurst R, Walgenbach A, Galili U (1998) Porcine cartilage transplants in the cynomolgus monkey. III. Transplantation of alpha-galactosidase-treated porcine cartilage. Transplantation 65(12):1577–1583
32. Stone KR, Walgenbach AW (1997) Surgical technique for articular cartilage transplantation to full thickness cartilage defects in the knee joint. Oper Tech Orthop 7(4):7
33. Stone KR, Walgenbach AW, Abrams JT, Nelson J, Gillett N, Galili U (1997) Porcine and bovine cartilage transplants in cynomolgus monkey: I. A model for chronic xenograft rejection. Transplantation 63(5):640–645
34. Stone KR, Walgenbach AW, Turek TJ, Somers DL, Wicomb W, Galili U (2007) Anterior cruciate ligament reconstruction with a porcine xenograft: a serologic, histologic, and biomechanical study in primates. Arthroscopy 23(4):411–419
35. Strickland SM, MacGillivray JD, Warren RF (2003) Anterior cruciate ligament reconstruction with allograft tendons. Orthop Clin N Am 34(1): 41–47
36. Weiss AB, Blazina ME, Goldstein AR, Alexander H (1985) Ligament replacement with an absorbable copolymer carbon fiber scaffold – early clinical experience. Clin Orthop Relat Res 196:77–85
37. Xu H, Wan H, Zuo W et al (2009) A porcine-derived acellular dermal scaffold that supports soft tissue regeneration: removal of terminal galactose-alpha-(1,3)-galactose and retention of matrix structure. Tissue Eng A 15(7):1807–1819
38. US Markets for Orthopedic Soft Tissue Solutions 2008 (2007). Toronto

Extra-articular Plasty with ACL Reconstruction: Long-Term Results of Associated Procedure

33

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33.1 Introduction

The aim of surgical management of the anterior cruciate ligament (ACL)-deficient knee is to restore knee stability, allowing return to activity and preventing secondary injury. While modern, intra-articular reconstruction techniques achieve good results for the majority of patients, they fail to restore normal knee biomechanics, particularly with regard to tibial rotation [1–5]. Residual pivot shift, a clinical manifestation of internal rotational laxity, is associated with poor outcomes and reduced patient satisfaction [6–8], and such altered kinematics may further contribute to the development of osteoarthritis [9–11].

ACL injury rarely occurs in isolation, and associated meniscal, chondral, and ligamentous lesions all influence the outcome of treatment [12]. Adding to this complexity, not all ACL-deficient knees will demonstrate symptomatic instability [13], and some knees may demonstrate a positive pivot shift despite an intact ACL [14].

Recently, there has been significant interest in the anatomy of the anterolateral structures of the knee and their role in the control of tibial internal rotation [15–21]. This, in turn, has led to renewed interest in the concept of lateral extra-articular reconstruction.

Lateral extra-articular procedures were designed to control anterolateral rotatory instability. Initially performed as isolated procedures, they were subsequently combined with intra-articular reconstructive techniques. Over time, they were largely abandoned due to concerns regarding their biomechanics and perceived non-anatomical nature, equivocal results, and the large-scale uptake of arthroscopic techniques. Today, the role of lateral extra-articular augmentation techniques is again being investigated, with the aim of reducing the failure rate of ACL reconstruction and improving rotational control.

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33.2 Historical Rationale for Extra-articular Reconstruction

Damage to the lateral structures of the knee in association with ACL injury was first described by Ségond in 1879 [22]. Working prior to the invention of radiographs, he noted an avulsion fracture of the anterolateral proximal tibia during cadaveric experiments to reproduce ACL injuries. He described a pearly, fibrous band attaching to this fragment, which detached from just behind the insertion of the iliotibial band (ITB).

In 1968, Slocum and Larson introduced the concept of rotatory instability in the ACL-deficient knee [23]. While their work primarily concerned external rotational abnormalities associated with combined medial injuries, other authors recognized the importance of abnormal internal rotation associated with lateral-sided injuries. Hughston, in 1976, described anterolateral rotatory instability and determined it to be caused primarily by a tear of the middle one-third of the lateral capsular ligament [24]. He noted that this instability may be accentuated by other ligament tears, in particular a tear of the ACL. In six acute cases, five were noted to have tears of this middle third of the capsular ligament at operation, with only one concurrent ACL tear. In 20 chronic cases, all had demonstrable laxity of the middle one-third capsular ligament at operation, and 15 had concurrent ACL tears. In 1979, Norwood reported the incidence of ligament injuries associated with anterolateral rotatory instability in 36 knees [25]. In six knees, there was an isolated injury to the anterolateral capsular ligament, in 26 a combined ACL and additional lateral injury (to the lateral capsular ligament, the iliotibial tract, or both), and in only four knees an isolated ACL injury identified. Jakob, in a cadaveric experiment, found the pivot shift in the ACL-deficient knee to be amplified by division of the middle third of the lateral capsular ligament [26]. As highlighted by Kennedy, the contemporary literature was flooded with conflicting reports as to the interpretation and management of acute and chronic ligamentous injuries, leading to “widespread debate and much confusion about the clinical manifestations and pathogenesis of anterior subluxation of the lateral tibial plateau” [27, 28].

Lateral extra-articular procedures were popularized around this time to address this anterolateral rotatory laxity or anterior subluxation of the lateral tibial plateau. As peripheral soft tissue injury was associated with anterolateral rotatory instability with or without a concurrent injury to the ACL [14, 24, 25], these techniques were believed to address the essential lesion of the condition. Furthermore, they were considered to have a clear biomechanical advantage over intra-articular reconstructions in controlling rotation, due to the longer lever arm of a peripherally based reconstruction to resist torque. Ellison described the ACL as “the hub of the wheel” and noted, “it is easier to control rotation of a wheel at its rim than at its hub” [29].

33.3 Extra-articular Procedures

The first lateral extra-articular procedure was described by Strickler in 1937 [30]. This combined intra- and extra-articular procedure utilized a loop of ITB routed through the knee and back over the anterolateral capsule and was used for both anterior and posterior cruciate insufficiencies. It was not for another 30 years that isolated lateral procedures would be introduced. Many procedures were described, with most being variations and modifications of the Lemaire and MacIntosh procedures [31].

33.4 Lemaire

In 1967, Marcel Lemaire of Paris published on the clinical presentation and treatment of chronic ruptures of the anterior cruciate ligament [32]. This article contained an accurate description of the pivot shift, as well as a description of an extra-articular procedure which he attributed to Cabot. In this procedure, a strip of posterior ITB was harvested and left attached distally at Gerdy’s tubercle. The strip was then wrapped around a nylon band, which was sutured into bone tunnels

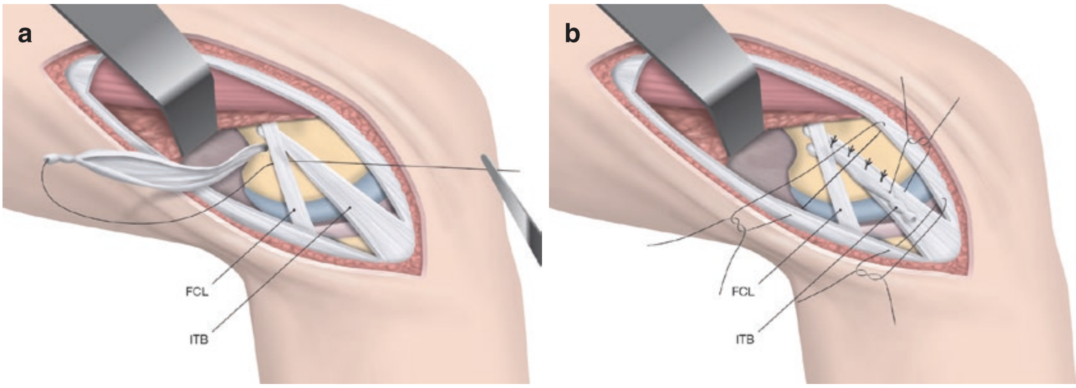

Fig. 33.1 The original Lemaire procedure. (**a**) Passing the the slip of ITB under LCL and through a bone tunnel posterior and proximal to the LCL origin, (**b**) folding the ITB slip back and suturing on to itself

at Gerdy's tubercle and just proximal to the origin of the lateral collateral ligament (LCL). Lemaire felt this operation was ideal to prevent the coupled anterior translation and internal rotation seen in the ACL-deficient knee, as intra-articular techniques were too difficult, available graft materials inadequate, and the results of such operations mediocre.

In 1975, Lemaire published the first description of his own extra-articular technique [33]. A 15 cm by 12 mm strip of the posterior ITB was harvested, again left attached distally at Gerdy's tubercle (Fig. 33.1). Just distal and deep to the origin of the LCL, an osseous tunnel was drilled, exiting on the posterior surface of the condyle very close to the capsular attachment. The ITB was passed through this tunnel and then back under the proximal LCL and sutured onto itself. The graft was secured with the knee held in full external rotation.

33.5 MacIntosh

At the Canadian Orthopaedic Association meeting in 1971, Galway and MacIntosh presented their description of the pivot shift, considered by many the first description of this phenomenon [34]. Included in this paper was a brief description of an extra-articular technique, using a strip of ITB routed under the LCL (Fig. 33.2). In 1976, MacIntosh presented the results of 90 cases operated using his technique [35]. Termed the "lateral substitution reconstruction for the anterior cruciate ligament," this procedure utilized a 20 cm strip of ITB, left attached at Gerdy's tubercle, which was routed under the LCL, through a subperiosteal tunnel and around the insertion of

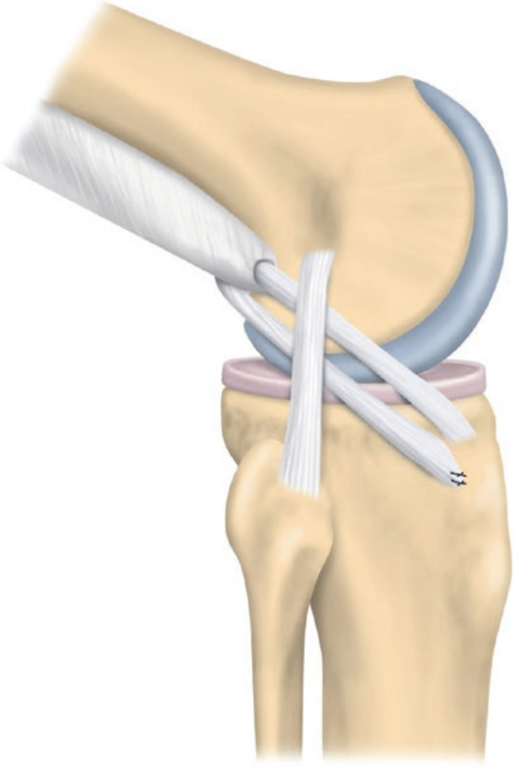

Fig. 33.2 The MacIntosh procedure

the lateral intermuscular septum, and finally back under the LCL. A combined intra- and extra-articular variant, with an intra-articular limb created by routing the graft “over the top” and through the knee, was also described. This procedure was later known as the MacIntosh II. A third procedure, the MacIntosh III, used a graft formed from the quadriceps tendon, prepatellar periosteum, and patellar tendon, in continuity and left attached distally. The graft was passed over the top from inside out.

33.6 Ellison

Ellison presented a description of his extra-articular procedure at the American Orthopedic Society for Sports Medicine meeting in 1975, before formally publishing the technique and results of his distal iliotibial band transfer in 1979 [36]. In his technique, the ITB was elevated from Gerdy’s tubercle with a button of bone, routed under the proximal LCL, and reattached at or just anteriorly to Gerdy’s tubercle with a staple. He also advocated plication of the middle third capsular ligament using a double breasted repair beneath the LCL (Fig. 33.3).

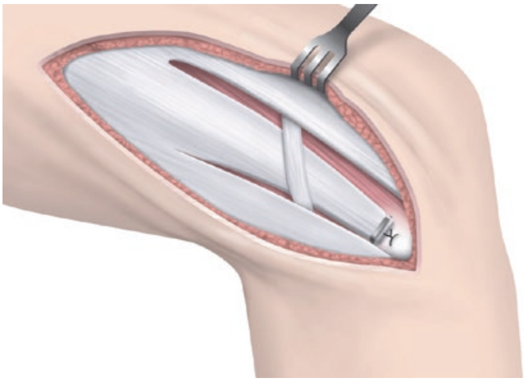

Fig. 33.3 The Ellison procedure

33.7 Current Techniques

Most modern techniques are modifications of the Lemaire and MacIntosh procedures. In general, these techniques do not double the graft back to the tibia and thus use a shorter ITB graft and require a shorter skin incision [37]. The graft may be passed over or under the LCL and affixed to the femur using a variety of methods, including a staple or interference screw.

Neyret has described a technique using a patellar tendon intra-articular graft and a gracilis tendon graft for the extra-articular component [38]. The gracilis is threaded through a drill hole in one of the bone blocks, creating one continuous graft. The patellar tendon graft is passed in an anterograde fashion, locking the gracilis tendon in the femoral tunnel with press fit of the bony block (Fig. 33.4). The two free limbs are then passed deep to the LCL and through either end of a bony tunnel through Gerdy’s tubercle.

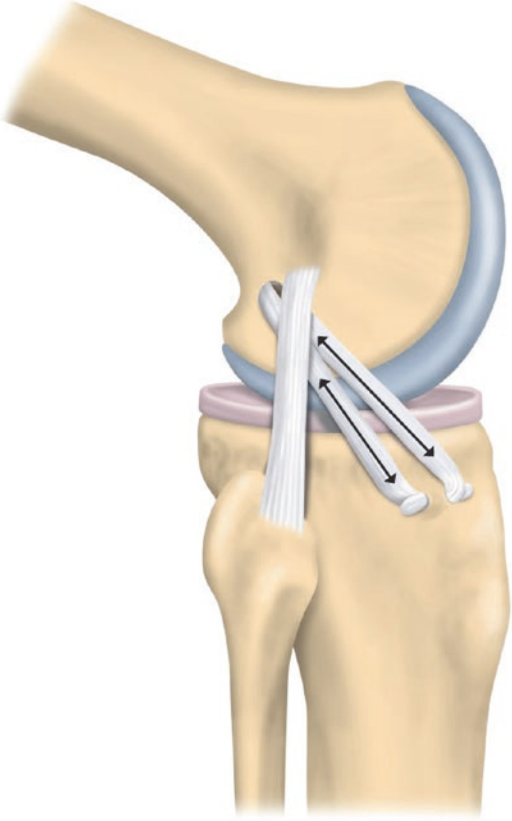

Fig. 33.4 The modified Lemaire procedure as described by Neyret et al.

33.8 Results for Isolated Lateral Extra-articular Procedures

The reported results for isolated extra-articular procedures are generally poor. Neyret reported the outcomes for an isolated Lemaire procedure in amateur skiers [39]. Of the 33 knees operated in 31 patients, only 16 were satisfied with the result. The pivot shift was positive in 9 of 18 at 1 year and 12 of 15 at final follow-up after 4.5 years. The outcome was noted to be dependent on the status of the medial meniscus, especially in those aged under 35 years.

Ireland and Trickey reported their results with the MacIntosh procedure in 50 knees at 2 years follow-up [40]. Anterolateral jerk was abolished in 42 of the 50 knees; however, less than half of their excellent and satisfactory results were able to return to sports at their previous level. Amirault reported the long-term results for this procedure, examining 27 patients at over 11 years follow-up [41]. Using their own 50-point scoring system based on patient function and clinical examination, 52 % of patients were rated as good or excellent. This report highlights the difficulty in comparing results from a period where many, predominantly non-validated outcome measures were used [42].

Ellison reported good or excellent results in 15 of 18 knees using his procedure with up to 41 months follow-up [36]. Other authors were unable to reproduce these results. Kennedy reported only 57 % good or excellent results with the procedure [28]. Twenty-four of 28 had a positive pivot shift at 6 months postoperatively, and all patients had a persistent anterior drawer. Fox reported 63 % fair or better results in 76 knees using a modification of Ellison's technique [43]. Reid reported the long-term results of the Ellison procedure in 32 patients with a mean follow-up of 11 years [44]. Seventy-five percent had a positive pivot shift, 56 % reported symptoms with activities of daily living, and only 24 % reported a good subjective outcome.

In addition to these poor clinical results, there were concerns regarding the biomechanics of these reconstructions. Several laboratory studies identified over-constraint of the lateral compartment, with the tibia held in an abnormal, externally rotated position at rest [45–47]. It was felt that this over-constraint would lead to either stretch of the graft over time or an increased rate of lateral compartment osteoarthritis. While graft elongation may certainly have contributed to the suboptimal clinical results, there is little evidence of increased lateral compartment degenerative change in the literature.

33.9 Current Evidence

33.9.1 Anatomy

Since Paul Ségond's description of a pearly band attaching to his eponymous fracture, numerous anatomical and radiological studies have described structures connecting the lateral femoral condyle, the lateral meniscus, and the lateral tibial plateau on the anterolateral aspect of the knee [22, 24, 48–53]. These structures have been described as capsular thickenings, components of the iliotibial tract, or ligaments in their own right and have been variously referred to as the "middle one-third of the lateral capsular ligament" or simply the "lateral capsular ligament" [24], the "capsulo-osseous layer of the iliotibial tract" [49], the "anterior oblique band" [51], and the "lateral femorotibial ligament" [52]. This non-standardized nomenclature and vague anatomical descriptions have contributed to ongoing confusion regarding the anatomy of the anterolateral knee.

The term "anterolateral ligament" (ALL) was probably first used by Kaplan in his 1962 study of the iliotibial tract [54]. The term was subsequently used by Terry to describe the function of the capsulo-osseous layer of the iliotibial tract [49] and again by Vincent to describe a structure running from the lateral femoral condyle to the lateral meniscus and anterolateral tibia, demonstrated by dissection from the intra-articular aspect of the joint capsule during total knee arthroplasty [53].

In 2013, Claes and colleagues published their landmark description of the anterolateral ligament (ALL) [15]. Identified in 40 of 41 specimens, this extra-capsular structure was found to originate just anterior to the LCL, posterior and proximal to the popliteus tendon insertion, and to insert onto the proximal tibia roughly midway between Gerdy's tubercle and the fibula head. The structure had a strong connection to the body of the lateral meniscus, but lacked attachments to the ITB.

Subsequently, a number of authors have contributed to our understanding of this structure with further anatomical and histological studies [16, 18, 20, 55] and descriptions of radiological landmarks [17, 19, 55]. While the tibial insertion is relatively constant in these descriptions, variation has been reported in the femoral attachment. Some studies have described the origin as being proximal and posterior to the LCL [20, 55], some anterior and distal [15, 16], while Caterine identified both variants [18]. Caterine also identified a peripheral nervous innervation, suggesting a role in proprioception.

These recent anatomical studies have helped to clarify the complex anatomy of the anterolateral knee and would suggest that lateral extra-articular procedures may be more anatomical than previously believed.

33.10 Native Knee Biomechanics

The anterior cruciate ligament is the primary restraint to anterior tibial translation. A number of structures contribute to the control of internal tibial rotation at the knee, including the ACL, the anterolateral ligament, the iliotibial band, the lateral meniscus [56], and the medial meniscotibial ligament [57].

Despite current interest in the ALL, to date relatively few biomechanical studies have been published. Kennedy examined the biomechanical properties and failure mechanism of the ALL [55]. They determined a mean maximum load of 175 N and stiffness of 20 N/mm. In 12 specimens, they identified four mechanisms of failure, ligamentous tear at the femoral attachment in four specimens, at the tibial insertion in one, in the mid-substance in four, and by a bony avulsion (i.e., Ségond fracture) in six, although it should be noted that the line of pull in these experiments was nonphysiologic. Regarding function, Dodds determined the ligament to be isometric from 0 to 60° of flexion and to lengthen with internal tibial rotation, strongly suggesting a role in rotational control [20]. Kittl studied the isometry of the native anterolateral structures as well as potential points for the fixation of an extra-articular reconstruction [58]. He found an ALL with an origin posterior and proximal to the LCL to be relatively isometric, while an ALL with a distal and anterior origin was lax approaching extension and unlikely to be effective in controlling the pivot shift [58]. Monaco examined the effect of cutting the ACL and lateral capsular ligament using a navigation system and manually applied forces [59]. His description of division of the lateral capsular ligament would have involved division of the ALL. He found an increase in internal rotation in all knee flexion angles in the ACL-deficient knee following division of the lateral capsular ligament, which was significant at 30° with an increase in internal rotation of 5.5°. Spencer investigated both sectioning and reconstruction of the ALL using navigation and manually applied forces. He measured an increase in internal rotation in extension of 2° after division of the ALL in the ACL-deficient knee while performing a simulated pivot shift [60]. Lording, in a cadaveric experiment using a robotic knee examination device, found division of the ALL in the ACL intact knee increased internal rotation at 30° of knee flexion by 2.4° [61]. However, there was wide variation in the effect of ALL sectioning between specimens, which in some specimens was not significant. Parsons, using a six degree of freedom robot, found the ALL to be the primary restraint to internal rotation at knee flexion angles greater than 35°, with the ACL providing the greatest restraint closer to extension [21]. It should be noted that the ITB was removed from all specimens in this study prior to testing. In contrast to Parsons, Kittl found the ALL played no significant role in internal rotational control [62]. In a similar robotic experiment, he determined the superficial and deep components of the ITB to be the primary restraints to internal rotation from 30 to 90°, with the ACL having a significant contribution at 0° only. Interestingly, the ACL provided no restraint to the pivot shift.

The finding of a role for the ITB in the control of internal tibial rotation is important but not new. Fetto was able to induce a pivot shift by division of the ITB in an ACL intact knee [14]. Jakob noted increased internal rotation but a paradoxical decrease in the pivot shift after division of Kaplan's fibers, reflecting the complex and multifactorial nature of these rotational abnormalities [26]. When he released the ITB distally by osteotomy of Gerdy's tubercle, the pivot shift became so marked in the ACL-deficient knee that the subluxation did not reduce before 60° of flexion. Gadikota, in a robotic study investigating the effect of increasing ITB load, found that internal rotation was significantly reduced between 20 and 30° of knee flexion with an ITB load of 50 N and from 15 to 30° with a load of 100 N [63]. Lording measured an increase in internal rotation of 2.6° in the ACL intact knee after division of the ITB at Gerdy's tubercle, slightly greater than that noted for the ALL and consistent across specimens [61].

33.11 Current Rationale for Lateral Extra-articular Procedures

Despite many advances in the evolution of anterior cruciate ligament surgery, failure remains an issue. While failure rates as high as 24% have been reported [64], recent large-scale cohort studies, systematic reviews, and registry reports would suggest a rate between 3.5% and 7% [65–67]. There is no universally accepted and applied definition of failure, however, and studies reporting failure rates using hard end-points such as revision reconstruction likely underestimate the true clinical burden. Pain, stiffness, ongoing instability, and an inability to return to sports may all signify a failed procedure, particularly as they relate to patient satisfaction.

It is now well understood that intra-articular ACL reconstruction does not restore normal knee biomechanics with regard to rotational control [1–5] and that this in turn has a negative impact on patient outcomes [6–8]. In an effort to better restore normal kinematics, various modifications of intra-articular techniques have been used.

In the double-bundle technique, the posterolateral bundle is intended to better restrain internal rotation and the pivot shift [68]. While time-zero biomechanical testing has suggested this technique offers superior rotational control than single-bundle techniques [69–71], clinical superiority has not been demonstrated [72–74].

In "anatomical" single-bundle reconstruction, the femoral tunnel is placed in the footprint of the native ACL, rather than the more vertical position seen in traditional techniques. This creates greater graft obliquity [75], which should theoretically better resist rotation and improve stability, although the results of biomechanical studies have been mixed [76–79]. While "anatomical" single-bundle techniques have demonstrated improved patient-reported outcomes compared to traditional techniques [80, 81], these more oblique grafts are subjected to higher in situ forces than more vertical grafts [82], which may lead to a higher graft failure rate [83].

Regardless of graft obliquity, the ACL is poorly positioned to resist internal rotation and probably contributes relatively little to rotational stability [62, 84]. As outlined above, recent anatomic and biomechanical data support the role of the anterolateral peripheral structures in rotational control. It is likely that damage to these peripheral restraints contributes to the variation in clinical laxity seen in the ACL-deficient knee [85, 86] and that failure to address these associated injuries contributes to residual rotatory laxity and poor outcomes [87]. In this light, repair or reconstruction of these structures could be considered more "anatomical" than intra-articular reconstruction alone.

Some biomechanical data is available to assess the effect of extra-articular augmentation on rotational control. Draganich studied the effect of both an isolated extra-articular reconstruction and a combined approach in a cadaveric model [88]. The isolated lateral procedure was found to over-constrain tibial internal rotation; however, when the lateral procedure was performed after an intra-articular reconstruction and care was taken not to tension the tenodesis with the knee in external rotation, both anterior translation and rotation were restored to that of the intact knee. In an in vivo study using intraoperative navigation, Monaco demonstrated reduced internal rotation after the augmentation of an intra-articular graft with a lateral extra-articular reconstruction [89]. This combination also showed improved rotational control compared to a double-bundle technique. Spencer examined the effect of an anatomical ALL reconstruction and a modified Lemaire extra-articular procedure in the ACL-deficient knee [60]. The anatomical ALL reconstruction, based on the landmarks of Claes [15], was ineffective in controlling internal rotation or anterior translation in an early phase pivot shift test, supporting the isometry findings of Kittl [58]. With the modified Lemaire reconstruction, however, there was a trend toward reduced internal rotation and a significant reduction in anterior translation.

One concern regarding extra-articular procedures is that this improved internal rotational control comes at the expense of over-constraint of the lateral compartment. While early studies of isolated procedures would support this [45–47], these techniques often called for graft fixation with the knee in maximal external rotation, and this finding was not borne out by Draganich for combined reconstructions [88]. In Kittl's recent study, graft passage deep to the LCL and attaching proximal to the lateral femoral condyle demonstrated near isometric behavior [58]. Both the MacIntosh and modified Lemaire demonstrated favorable length change behavior. Similarly, there is no evidence that lateral extra-articular procedures cause increased lateral compartment osteoarthritis. Zaffagnini, in a randomized trial comparing patellar tendon, four-strand hamstring, and Marcacci's combined technique, noted no differences in radiological outcomes at 5 years [90].

Lateral extra-articular procedures may also work synergistically to reduce the failure rate for ACL reconstructions. Terry described the ACL and the capsulo-osseous layer of the ITB as forming an "inverted U" behind the lateral femoral condyle, supporting the condyle and preventing posterior subluxation on the stabilized tibia [85]. Draganich demonstrated load sharing between intra-articular and extra-articular reconstructions in a cadaveric model [88]. Similarly, Engebretsen found that an iliotibial tenodesis reduced the forces seen in an ACL graft by 43 % [47]. These studies suggest that the addition of an extra-articular procedure could shield an intra-articular reconstruction from excessive forces during the healing phase, potentially protecting it from early stretch or fixation failure and reducing the rate of re-injury in the long term. This may be of particular importance for more grafts likely to see higher forces, such as more oblique single-bundle grafts and patients after medial meniscectomy [91], as well as patient groups at higher risk of failure, such as younger and female patients [66, 92, 93].

33.12 Results for Combined Intra- and Extra-articular Procedures

The first combined procedures were performed soon after the emergence of lateral extra-articular techniques. Some, such as the MacIntosh II, were inherently combined procedures, while others involved the augmentation of an intra-articular reconstruction with a separate lateral procedure.

The early results for combined procedures were encouraging. Bertoia reported good or excellent results in 31 of 34 knees using the MacIntosh lateral substitution over-the-top repair (MacIntosh II), with the pivot shift abolished in 91 % [94]. Zarins and Rowe described a modification of MacIntosh's over-the-top procedure, with an ITB graft passing from outside in supplemented by the addition of a distally based semitendinosus graft passing from inside out [95]. Eighty-eight of 100 patients reported good or excellent satisfaction with the procedure, with pivot shift reduced to grade 0 or 1+ in 91.

Augmentation procedures also showed promising results. Dejour studied 251 cases operated with a patellar tendon intra-articular reconstruction augmented with the Lemaire procedure [96]. Eighty-three percent had good or excellent functional results, although the pivot shift was described as equivocal in 24 %. Rackemann reported the results of 714 knees treated with a medial third patellar tendon reconstruction augmented with a MacIntosh procedure [97]. At 6 years, results were satisfactory in 93 %, with only one positive pivot shift.

The first comparative study of intra- and extra-articular reconstruction versus intra-articular reconstruction alone was published by Jensen in 1983 [98]. In this retrospective study, he found the combined procedure group showed the most marked reduction in anterolateral laxity. Subsequent studies, however, challenged the superiority of combined procedures. Strum reported no benefit of combined procedures over isolated intra-articular reconstructions, stressing the importance of a well-performed intra-articular procedure [99]. O'Brien found no difference in clinical stability for those treated with a central third patellar tendon intra-articular graft with or without the addition of a lateral extra-articular sling procedure; however, 40 % of the extra-articular group had chronic pain or swelling associated with the additional procedure [100]. In the first English language, randomized, prospective study, Anderson compared patellar tendon, hamstring, and hamstring combined with lateral extra-articular procedures and found no benefit to the addition of the extra-articular reconstruction [101].

By this stage, lateral extra-articular reconstructions had been largely abandoned, although a number of centers, particularly in Europe, continued to utilize the technique. Some long-term case series are available from these institutions.

In Lyon, France, both Lerat and Neyret have published long-term results for combined procedures. Lerat reported the results for 138 patients at a mean follow-up of 11.7 years [102]. Patients were treated with a "MacInJones" procedure, in which an intra-articular patellar tendon graft was augmented by an extra-articular reconstruction performed with a strip of quadriceps tendon in continuity with the patellar tendon graft. International Knee Documentation Committee (IKDC) functional results were good or excellent in 60 %. The pivot shift was negative in 66 %, grade 1+ in 30 %, and grade 2+ in 4 %. There were 12 graft failures. Pernin and Neyret reported the long-term outcomes of 100 patients treated by Henri Dejour with a patellar tendon intra-articular reconstruction and a modified Lemaire procedure, at a mean follow-up of 24.5 years and with particular respect to the risk factors for the development of osteoarthritis [103]. The intra-articular reconstruction was performed in an open fashion through an anteromedial arthrotomy. Seventy-four percent reported their outcome to be good or excellent, with IKDC assessment normal or near normal in 46 %. The pivot shift was negative in 77 %, with 17 % having a moderate pivot (2+) and 6 % a gross pivot (3+). Radiographically, the percentage of knees without degenerative changes was stable from 11.5 years (41 %) to 24.5 years (39 %); however, among those with degenerative changes, the proportion with severe osteoarthritis increased from 10 % to 27 %. Both medial meniscectomy and medial articular cartilage lesions at the time of surgery were predictive of the development of osteoarthritis, as were increased age at operation and increased delay between injury and surgery. Residual laxity was not found to correlate with the radiological outcome; however, only anterior translation and not rotatory laxity was assessed.

In Italy, Marcacci described a technique not dissimilar to the hamstring arm of the Zarins-Rowe procedure [104]. The gracilis and semitendinosus tendons are harvested with their tibial insertions maintained. The graft is passed through a tibial bone tunnel and then over the top of the lateral condyle from inside out. The tendons are affixed in a groove on the lateral femur with two staples, and the remaining graft passed deep to the LCL and attached at Gerdy's tubercle. At 11-year follow-up in 54 knees in high-level sports participants, 90.7 % achieved good or excellent International Knee Documentation Committee (IKDC) scores, with three knees showing a slight residual pivot shift [105]. No increase in osteoarthritis was noted for this combined procedure compared to historical controls.

A number of small, randomized studies comparing combined versus isolated intra-articular reconstruction have been published [90, 101, 106–111]. These are summarized in Table 33.1. Ait Si Selmi evaluated the outcomes of 120 patients randomized to receive either a patellar tendon

Table 33.1 Summary of results of studies comparing ACL reconstruction with and without lateral extra-articular tenodesis

Study	Year	Country	Combined reconstruction (intra + extra-articular)	Isolated intra-articular reconstruction	Mean follow-up (years)	Conclusion	Reason	Level of evidence
Anderson et al. [101]	2001	USA	Hamstrings, single bundle + Losee ($n=34$)	Patellar tendon ($n=35$) and hamstrings, single bundle ($n=33$)	3	No significant difference		I
Ait Si Selmi et al. [106]	2002	France	Patellar tendon + hamstring ($n=60$)	Patellar tendon ($n=60$)	1.5	No significant difference		II
Acquitter et al. [107]	2003	France	"MacInJones" patellar tendon + quadriceps tendon ($n=50$)	Patellar tendon ($n=50$)	4.8	No significant difference		I
Giraud et al. [108]	2006	France	"MacInJones" patellar tendon + quadriceps tendon ($n=29$)	Patellar tendon ($n=34$)	7	No significant difference		II
Zaffagnini et al. [90]	2006	Italy	Marcacci hamstrings ($n=25$)	Patellar tendon ($n=25$) and hamstrings, single bundle ($n=25$)	5	Favors combined reconstruction	Higher median IKDC subjective score	I
Zaffagnini et al. [109]	2008	Italy	Marcacci hamstrings ($n=35$)	Hamstrings, double bundle ($n=37$)	3	Favors isolated intra-articular reconstruction	Improved IKDC, ROM, activity scores	II
Vadalà et al. [110]	2013	Italy	Hamstrings, single bundle + Cocker-Arnold (modified MacIntosh) ($n=28$)	Hamstrings, single bundle ($n=32$)	3.7	Favors combined reconstruction	Reduced residual pivot shift	I
Trichine et al. [111]	2014	Algeria	Patellar tendon + modified Lemaire ($n=60$)	Patellar tendon ($n=60$)	2	No significant difference		I

intra-articular reconstruction or Neyret's combined procedure [106]. The combined group showed improved satisfaction, IKDC subjective scores, and improved control of the pivot shift, although these differences did not reach statistical significance. The study of Giraud reports the medium-term results of 63 patients treated with either the "MacInJones" or a patellar tendon reconstruction at 7 years [108]. While there was a trend toward improved IKDC scores and a reduction in pivot shift seen in the extra-articular group, this did not reach statistical significance in this small trial.

A recent systematic review and meta-analysis by Hewison found a significant reduction in the pivot shift for combined procedures compared to intra-articular reconstruction alone, although this did not translate into improved IKDC scores [112]. The quality of included studies, however, was poor, with an unclear to high risk of bias for most articles. In a similar meta-analysis, Rezende found improved pivot shift and Lachman test results for combined procedures, with no difference in functional outcomes [113].

Currently, a large, multicenter, prospective randomized trial is underway, comparing intra-articular versus combined intra-and extra-articular reconstruction in a young, high-risk population (Getgood et al. ISAKOS Multicentre Grant Award 2013).

33.13 Indications for Extra-articular Reconstructions

The results of intra-articular reconstruction are satisfactory for the majority of patients, and as such extra-articular reconstruction should be reserved for those most likely to benefit from the additional intervention. This may include those at higher risk of failure, such as younger patients [93] and those returning to pivoting sports [114]. A high degree of clinical laxity, associated ligamentous or meniscal injury patterns, and revision reconstruction may also be appropriate indications.

Clinical, radiological, and even intraoperative navigation-based criteria have been proposed to help identify patients based on their degree of laxity [108, 115, 116]. It is likely, however, that some of the variation in clinical laxity seen in the ACL-deficient knee is related to associated injuries [85]. LaPrade achieved 95 % accuracy in diagnosing injury to the meniscotibial portion of the mid-third lateral capsular ligament using magnetic resonance imaging [50], and Claes has also identified a high rate of ALL abnormalities in association with ACL injury [86]. Advances in imaging techniques and technology may allow for accurate diagnosis and targeted treatment strategies for these injuries.

Another associated injury that may be an appropriate indication is medial meniscal lesions requiring meniscectomy. Loss of the medial meniscus increases graft forces by up to 50 % [91] and is associated with reduced IKDC scores and inferior pivot shift control after ACL reconstruction [117].

The results for revision ACL reconstruction are generally inferior to those for primary procedures this may also be an indication for extra-articular augmentation. Trojani reported a multicenter series of 189 revision procedures, of which 26 included a lateral extra-articular reconstruction [118]. While the pivot shift was better controlled and there was a trend toward a lower failure rate in the extra-articular group, there was no difference in IKDC scores.

Conclusion

Lateral extra-articular procedures are effective in controlling internal rotation at the knee, with recent anatomical and biomechanical studies supporting the rationale for their use in selected cases. In combination with intra-articular reconstruction, these procedures may have a role in specific high-risk and/or revision scenarios; however, further research is needed to better clarify these indications.

References

1. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH (2002) The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon a cadaveric study comparing anterior tibial and rotational loads. J Bone Joint Surg Am 84(6):907–914

2. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SLY (2003) Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. Arthroscopy 19(3):297–304. doi:10.1053/jars.2003.50084
3. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983. doi:10.1177/0363546503261709
4. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD (2005) Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. Arthroscopy 21(11):1323–1329. doi:10.1016/j.arthro.2005.08.032
5. Georgoulis AD, Ristanis S, Chouliaras V, Moraiti C, Stergiou N (2007) Tibial rotation is not restored after ACL reconstruction with a hamstring graft. Clin Orthop Relat Res 454:89–94. doi:10.1097/BLO.0b013e31802b4a0a
6. Kocher MS, Steadman JR, Briggs K, Zurakowski D, Sterett WI, Hawkins RJ (2002) Determinants of patient satisfaction with outcome after anterior cruciate ligament reconstruction. J Bone Joint Surg Am 84-A(9):1560–1572
7. Ayeni OR, Chahal M, Tran MN, Sprague S (2012) Pivot shift as an outcome measure for ACL reconstruction: a systematic review. Knee Surg Sports Traumatol Arthrosc 20(4):767–777. doi:10.1007/s00167-011-1860-y
8. Crawford SN, Waterman BR, Lubowitz JH (2013) Long-term failure of anterior cruciate ligament reconstruction. Arthroscopy 29(9):1566–1571. doi:10.1016/j.arthro.2013.04.014
9. Jonsson H, Riklund-Ahlström K, Lind J (2004) Positive pivot shift after ACL reconstruction predicts later osteoarthrosis: 63 patients followed 5–9 years after surgery. Acta Orthop Scand 75(5):594–599. doi:10.1080/00016470410001484
10. Lohmander LS, Englund PM, Dahl LL, Roos EM (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769. doi:10.1177/0363546507307396
11. Haughom B, Schairer W, Souza RB, Carpenter D, Ma CB, Li X (2012) Abnormal tibiofemoral kinematics following ACL reconstruction are associated with early cartilage matrix degeneration measured by MRI T1rho. Knee 19(4):482–487. doi:10.1016/j.knee.2011.06.015
12. George MS, Dunn WR, Spindler KP (2006) Current concepts review: revision anterior cruciate ligament reconstruction. Am J Sports Med 34(12):2026–2037. doi:10.1177/0363546506295026
13. Noyes FR, Matthews DS, Mooar PA, Grood ES (1983) The symptomatic anterior cruciate-deficient knee. Part II: the results of rehabilitation, activity modification, and counseling on functional disability. J Bone Joint Surg Am 65(2):163–174
14. Fetto JF, Marshall JL (1979) Injury to the anterior cruciate ligament producing the pivot-shift sign. J Bone Joint Surg Am 61(5):710–714
15. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J (2013) Anatomy of the anterolateral ligament of the knee. J Anat 223(4):321–328. doi:10.1111/joa.12087
16. Helito CP, Demange MK, Bonadio MB, et al (2013) Anatomy and histology of the knee anterolateral ligament. Orthopaedic J Sports Med;1(7). doi:10.1177/2325967113513546
17. Helito CP, Demange MK, Bonadio MB et al (2014) Radiographic landmarks for locating the femoral origin and tibial insertion of the knee anterolateral ligament. Am J Sports Med 42(10):2356–2362. doi:10.1177/0363546514543770
18. Caterine S, Litchfield R, Johnson M, Chronik B, Getgood A (2014) A cadaveric study of the anterolateral ligament: re-introducing the lateral capsular ligament. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3117-z
19. Rezansoff AJ, Caterine S, Spencer L, Tran MN, Litchfield RB, Getgood AM (2014) Radiographic landmarks for surgical reconstruction of the anterolateral ligament of the knee. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3126-y
20. Dodds AL, Halewood C, Gupte CM, Williams A, Amis AA (2014) The anterolateral ligament: anatomy, length changes and association with the Segond fracture. Bone Joint J 96-B(3):325–331. doi:10.1302/0301-620X.96B3.33033
21. Parsons EM, Gee AO, Spiekerman C, Cavanagh PR (2015) The biomechanical function of the anterolateral ligament of the knee. Am J Sports Med 43(3):669–674. doi:10.1177/0363546514562751
22. Ségond P (1879) Recherches Cliniques Et Expérimentales Sur Les Épanchements Sanguins Du Genou Par Entorse. Prog Méd 7:297–341
23. Slocum DB, Larson RL (1968) Rotatory instability of the knee. Its pathogenesis and a clinical test to demonstrate its presence. J Bone Joint Surg Am 50(2):211–225
24. Hughston JC, Andrews JR, Cross MJ, Moschi A (1976) Classification of knee ligament instabilities. Part II. The lateral compartment. J Bone Joint Surg 58(2):173–179, message:%3C8DC7539A701A5041A0044BDB4266B03F64454697@MELEXC01.surgeons.org%3E
25. Norwood LA, Andrews JR, Meisterling RC, Glancy GL (1979) Acute anterolateral rotatory instability of the knee. J Bone Joint Surg Am 61(5):704–709
26. Jakob RP, Hassler H, Staeubli HU (1981) 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 191:1–32
27. Kennedy JC, Fowler PJ (1971) Medial and anterior instability of the knee. J Bone Joint Surg Am. doi:10.1148/rg.2015140166

28. Kennedy JC, Stewart R, Walker DM (1978) Anterolateral rotatory instability of the knee joint. An early analysis of the Ellison procedure. J Bone Joint Surg Am 60(8):1031–1039
29. Ellison AE (1978) Anterolateral rotatory instability. In: Funk FJ Jr, (ed) Symposium on the athlete's knee, surgical repair and reconstruction. Vol Am Acad Orthop Surg pp 178–193
30. Strickler FP (1937) A satisfactory method of repairing crucial ligaments. Ann Surg 105(6):912–916. doi:10.1007/s00705-014-2107-2
31. Schindler OS (2011) Surgery for anterior cruciate ligament deficiency: a historical perspective. Knee Surg Sports Traumatol Arthrosc 20(1):5–47. doi:10.1007/s00167-011-1756-x
32. Lemaire M (1967) Ruptures anciennes du ligament croise anterieur du genou. J Chir 93:311–320
33. Lemaire M (1975) Instabilité chronique du genou. Techniques et résultats des plasties ligamentaires en traumatologie sportive. J Chir (Paris) 110(4): 281–294
34. Galway RD, Beaupre A, MacIntosh DL (1972) Pivot shift: a clinical sign of symptomatic anterior cruciate insufficiency. J Bone Joint Surg Br 54:763–764
35. MacIntosh DL (1976) Lateral substitution reconstruction. J Bone Joint Surg Br 58-B(1):142
36. Ellison AE (1979) Distal iliotibial-band transfer for anterolateral rotatory instability of the knee. J Bone Joint Surg Am 61(3):330–337
37. Christel P, Djian P (2002) Plastie extra-articulaire antéro-latérale du genou utilisant une ténodèse courte au fascia lata. Revue de Chirurgie Orthopédique et Traumatologique 88(5):508–513
38. Neyret P, Demey G, Servien E, Lustig S (2012) Traité De Chirurgie De Genou. Elsevier, Masson
39. Neyret P, Palomo JR, Donell ST, Dejour H (1994) Extra-articular tenodesis for anterior cruciate ligament rupture in amateur skiers. Br J Sports Med 28(1):31–34
40. Ireland J, Trickey EL (1980) Macintosh tenodesis for anterolateral instability of the knee. J Bone Joint Surg Br 62(3):340–345
41. Amirault JD, Cameron JC, MacIntosh DL, Marks P (1988) Chronic anterior cruciate ligament deficiency. Long-term results of MacIntosh's lateral substitution reconstruction. J Bone Joint Surg Br 70(4):622–624. doi:10.6026/97320630009622
42. Johnson DS, Smith RB (2001) Outcome measurement in the ACL deficient knee – what's the score? Knee 8(1):51–57
43. Fox JM, Blazina ME, Del Pizzo W, Ivey FM, Broukhim B (1980) Extra-articular stabilization of the knee joint for anterior instability. Clin Orthop Relat Res 147:56–61
44. Reid JS, Hanks GA, Kalenak A, Kottmeier S (1992) The Ellison iliotibial-band transfer for a torn anterior cruciate ligament of the knee. Long-term follow-up. J Bone Joint Surg AM 74(9):1392–402
45. Sydney SV, Haynes DW, Hungerford DS, Gerdes MH (1987) The altered kinematic effect of an iliotibial band tenodesis on the anterior cruciate deficient knee. Orthop Res Soc Trans Annu Meet 340
46. Draganich LF, Reider B, Miller PR (1989) An in vitro study of the Müller anterolateral femorotibial ligament tenodesis in the anterior cruciate ligament deficient knee. Am J Sports Med 17(3):357–362
47. Engebretsen L, Lew WD, Lewis JL, Hunter RE (1990) The effect of an iliotibial tenodesis on intraarticular graft forces and knee joint motion. Am J Sports Med 18(2):169–176
48. Johnson LL (1979) Lateral capsular ligament complex: anatomical and surgical considerations. Am J Sports Med 7:156
49. Terry GC, Hughston JC, Norwood LA (1986) The anatomy of the iliopatellar band and iliotibial tract. Am J Sports Med 14(1):39–45
50. LaPrade RF, Gilbert TJ, Bollom TS, Wentorf F, Chaljub G (2000) The magnetic resonance imaging appearance of individual structures of the posterolateral knee. A prospective study of normal knees and knees with surgically verified grade III injuries. Am J Sports Med 28(2):191–199
51. Campos JC, Chung CB, Lektrakul N et al (2001) Pathogenesis of the segond fracture: anatomic and MR imaging evidence of an iliotibial tract or anterior oblique band Avulsion1. Radiology 219(2):381–386
52. Vieira ELC, Vieira EÁ, Teixeira da Silva R, Santos Berlfein dos PA, Abdalla RJ, Cohen M (2007) An anatomic study of the iliotibial tract. Arthroscopy 23(3):269–274. doi:10.1016/j.arthro.2006.11.019
53. Vincent J-P, Magnussen RA, Gezmez F et al (2011) The anterolateral ligament of the human knee: an anatomic and histologic study. Knee Surg Sports Traumatol Arthrosc 20(1):147–152. doi:10.1007/s00167-011-1580-3
54. Kaplan EB (1962) Some aspects of functional anatomy of the human knee joint. Clin Orthop 23:18–29
55. Kennedy MI, Claes S, Fuso FAF et al (2015) The anterolateral ligament: an anatomic, radiographic, and biomechanical analysis. Am J Sports Med 43(7):1606–1615. doi:10.1177/0363546515578253
56. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD (2010) The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 38(8):1591–1597. doi:10.1177/0363546510364402
57. Peltier A, Lording T, Maubisson L, Ballis R, Neyret P, Lustig S (2015) The role of the meniscotibial ligament in posteromedial rotational knee stability. Knee Surg Sports Traumatol Arthrosc 1–7. doi: 10.1007/s00167-015-3751-0
58. Kittl C, Halewood C, Stephen JM et al (2015) Length change patterns in the lateral extra-articular structures of the knee and related reconstructions. Am J Sports Med 43(2):354–362. doi:10.1177/0363546514560993
59. Monaco E, Ferretti A, Labianca L et al (2011) Navigated knee kinematics after cutting of the ACL and its secondary restraint. Knee Surg Sports Traumatol Arthrosc 20(5):870–877. doi:10.1007/s00167-011-1640-8

60. Spencer L, Burkhart TA, Tran MN et al (2015) Biomechanical analysis of simulated clinical testing and reconstruction of the anterolateral ligament of the knee. Am J Sports Med. doi:10.1177/0363546515589166
61. Lording TD, Stinton S, DeJarnette N, Madden C, Neyret P, Branch TP The effect of cutting and repair of the anterolateral ligament and iliotibial band on tibial axial rotation. Presented at: Asia-Pacific Orthopaedic Association Congress, Melbourne Australia, 29 March-1 April 2016
62. Kittl C, Daou El H, Athwal KK, et al (2016) The Role of the Anterolateral Structures and the ACL in Controlling Laxity of the Intact and ACL-Deficient Knee. Am J Sports Med 44(2):345–354
63. Gadikota HR, Kikuta S, Qi W, Nolan D, Gill TJ, Li G (2013) Effect of increased iliotibial band load on tibiofemoral kinematics and force distributions: a direct measurement in cadaveric knees. J Orthop Sports Phys Ther 43(7):478–485. doi:10.2519/jospt.2013.4506
64. Barrett GR, Luber K, Replogle WH, Manley JL (2010) Allograft anterior cruciate ligament reconstruction in the young, active patient: tegner activity level and failure rate. Arthroscopy 26(12):1593–1601. doi:10.1016/j.arthro.2010.05.014
65. Wright RW, Magnussen RA, Dunn WR, Spindler KP (2011) Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. J Bone Joint Surg Am 93(12):1159–1165. doi:10.2106/JBJS.J.00898
66. Magnussen RA, Lawrence JTR, West RL, Toth AP, Taylor DC, Garrett WE (2012) Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. Arthroscopy 28(4):526–531. doi:10.1016/j.arthro.2011.11.024
67. Swedish ACL Register. Annual Report 2013. 2014:1–36
68. Zelle BA, Vidal AF, Brucker PU, Fu FH (2007) Double-bundle reconstruction of the anterior cruciate ligament: anatomic and biomechanical rationale. J Am Acad Orthop Surg 15(2):87–96
69. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SLY (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30(5):660–666
70. Plaweski S, Grimaldi M, Courvoisier A, Wimsey S (2011) Intraoperative comparisons of knee kinematics of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19(8):1277–1286. doi:10.1007/s00167-011-1405-4
71. Lee S, Kim H, Jang J, Seong SC, Lee MC (2012) Comparison of anterior and rotatory laxity using navigation between single- and double-bundle ACL reconstruction: prospective randomized trial. Knee Surg Sports Traumatol Arthrosc 20(4):752–761. doi:10.1007/s00167-012-1880-2
72. Meredick RB, Vance KJ, Appleby D, Lubowitz JH (2008) Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis. Am J Sports Med 36(7):1414–1421. doi:10.1177/0363546508317964
73. Ahlden M, Samuelsson K, Sernert N, Forssblad M, Karlsson J, Kartus J (2012) The swedish national anterior cruciate ligament register: a report on baseline variables and outcomes of surgery for almost 18,000 patients. Am J Sports Med 40(10):2230–2235. doi:10.1177/0363546512457348
74. Song EK, Seon JK, Yim JH, Woo SH, Seo HY, Lee KB (2013) Progression of osteoarthritis after double- and single-bundle anterior cruciate ligament reconstruction. Am J Sports Med 41(10):2340–2346. doi:10.1177/0363546513498998
75. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ (2010) Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: a cadaveric study of femoral tunnel length and obliquity. Arthroscopy 26(3):342–350. doi:10.1016/j.arthro.2009.12.006
76. Kato Y, Ingham SJM, Kramer S, Smolinski P, Saito A, Fu FH (2009) Effect of tunnel position for anatomic single-bundle ACL reconstruction on knee biomechanics in a porcine model. Knee Surg Sports Traumatol Arthrosc 18(1):2–10. doi:10.1007/s00167-009-0916-8
77. Markolf KL, Jackson SR, McAllister DR (2010) A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test. Am J Sports Med 38(5):912–917. doi:10.1177/0363546509358321
78. Kondo E, Merican AM, Yasuda K, Amis AA (2011) Biomechanical comparison of anatomic double-bundle, anatomic single-bundle, and nonanatomic single-bundle anterior cruciate ligament reconstructions. Am J Sports Med 39(2):279–288. doi:10.1177/0363546510392350
79. Webster KE, Wotherspoon S, Feller JA, McClelland JA (2012) The effect of anterior cruciate ligament graft orientation on rotational knee kinematics. Knee Surg Sports Traumatol Arthrosc 21(9):2113–2120. doi:10.1007/s00167-012-2310-1
80. Jepsen CF, Lundberg-Jensen AK, Faunoe P (2007) Does the position of the femoral tunnel affect the laxity or clinical outcome of the anterior cruciate ligament–reconstructed knee? A clinical, prospective, randomized, double-blind study. Arthroscopy 23(12):1326–1333. doi:10.1016/j.arthro.2007.09.010
81. Lee MC, Seong SC, Lee S et al (2007) Vertical femoral tunnel placement results in rotational knee laxity after anterior cruciate ligament reconstruction. Arthroscopy 23(7):771–778. doi:10.1016/j.arthro.2007.04.016
82. Kato Y, Maeyama A, Lertwanich P et al (2012) Biomechanical comparison of different graft positions for single-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21(4):816–823. doi:10.1007/s00167-012-1951-4

83. Clatworthy M, Pearle A, Williams A, Lind M. Femoral Tunnel Placement in ACL reconstruction Central Footprint vs AM Bundle. ISAKOS Newsletter 2015 Vol 2
84. Oh YK, Kreinbrink JL, Ashton-Miller JA, Wojtys EM (2011) Effect of ACL transection on internal tibial rotation in an in vitro simulated pivot landing. J Bone Joint Surg Am 93(4):372–380. doi:10.2106/JBJS.J.00262
85. Terry GC, Norwood LA, Hughston JC, Caldwell KM (1993) How iliotibial tract injuries of the knee combine with acute anterior cruciate ligament tears to influence abnormal anterior tibial displacement. Am J Sports Med 21(1):55–60
86. Claes S, Bartholomeeusen S, Bellemans J (2014) High prevalence of anterolateral ligament abnormalities in magnetic resonance images of anterior cruciate ligament-injured knees. Acta Orthop Belg 80(1):45–49
87. Harner CD, Giffin JR, Dunteman RC, Annunziata CC, Friedman MJ (2001) Evaluation and treatment of recurrent instability after anterior cruciate ligament reconstruction. Instr Course Lect 50:463–474
88. Draganich LF, Reider B, Ling M, Samuelson M (1990) An in vitro study of an intraarticular and extraarticular reconstruction in the anterior cruciate ligament deficient knee. Am J Sports Med 18(3):262–266
89. Monaco E, Labianca L, Conteduca F, De Carli A, Ferretti A (2007) Double bundle or single bundle plus extraarticular tenodesis in ACL reconstruction? Knee Surg Sports Traumatol Arthrosc 15(10):1168–1174. doi:10.1007/s00167-007-0368-y
90. Zaffagnini S, Marcacci M, Presti Lo M, Giordano G, Iacono F, Neri MP (2006) Prospective and randomized evaluation of ACL reconstruction with three techniques: a clinical and radiographic evaluation at 5 years follow-up. Knee Surg Sports Traumatol Arthrosc 466(11):1060–1069. doi:10.1007/s00167-006-0130-x
91. Papageorgiou CD, Gil JE, Kanamori A, Fenwick JA, Woo SL, Fu FH (2001) The biomechanical interdependence between the anterior cruciate ligament replacement graft and the medial meniscus. Am J Sports Med 29(2):226–231
92. Barrett AM, Craft JA, Replogle WH, Hydrick JM, Barrett GR (2011) Anterior cruciate ligament graft failure: a comparison of graft type based on age and tegner activity level. Am J Sports Med 39(10):2194–2198. doi:10.1177/0363546511415655
93. Webster KE, Feller JA, Leigh WB, Richmond AK (2014) Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J Sports Med 42(3):641–647. doi:10.1177/0363546513517540
94. Bertoia JT, Urovitz EP, Richards RR, Gross AE (1985) Anterior cruciate reconstruction using the MacIntosh lateral-substitution over-the-top repair. J Bone Joint Surg Am 67(8):1183–1188
95. Zarins B, Rowe CR (1986) Combined anterior cruciate-ligament reconstruction using semitendinosus tendon and iliotibial tract. J Bone Joint Surg Am 68(2):160–177
96. Dejour H, Walch G, Neyret P, Adeleine P (1988) Results of surgically treated chronic anterior laxities: apropos of 251 cases reviewed with a minimum follow-up of 3 years. Rev Chir Orthop Reparatrice Appar Mot 74:622–636
97. Rackemann S, Robinson A, Dandy DJ (1991) Reconstruction of the anterior cruciate ligament with an intra-articular patellar tendon graft and an extra-articular tenodesis. Results after six years. J Bone Joint Surg Br 73(3):368–373
98. Jensen JE, Slocum DB, Larson RL, James SL, Singer KM (1983) Reconstruction procedures for anterior cruciate ligament insufficiency: a computer analysis of clinical results. Am J Sports Med 11(4):240–248
99. Strum GM, Fox JM, Ferkel RD et al (1989) Intraarticular versus intraarticular and extraarticular reconstruction for chronic anterior cruciate ligament instability. Clin Orthop Relat Res 245:188–198
100. O'Brien SJ, Warren RF, Wickiewicz TL et al (1991) The iliotibial band lateral sling procedure and its effect on the results of anterior cruciate ligament reconstruction. Am J Sports Med 19(1):21–24; discussion 24–25
101. Anderson AF, Snyder RB, Lipscomb AB (2001) Anterior cruciate ligament reconstruction a prospective randomized study of three surgical methods. Am J Sports Med 29(3):272–279
102. Lerat J-L, Chotel F, Besse JL et al (1998) The results after 10–16 years of the treatment of chronic anterior laxity of the knee using reconstruction of the anterior cruciate ligament with a patellar tendon graft combined with an external extra-articular reconstruction. Rev Chir Orthop Reparatrice Appar Mot 84(8):712–727. doi:10.1016/j.foodchem.2015.05.124
103. Pernin J, Verdonk P, Si Selmi TA, Massin P, Neyret P (2010) Long-term follow-up of 24.5 years after intra-articular anterior cruciate ligament reconstruction with lateral extra-articular augmentation. Am J Sports Med 38(6):1094–1102. doi:10.1177/0363546509361018
104. Marcacci M, Zaffagnini S, Iacono F, Neri MP, Loreti I, Petitto A (1998) Arthroscopic intra- and extra-articular anterior cruciate ligament reconstruction with gracilis and semitendinosus tendons. Knee Surg Sports Traumatol Arthrosc 6(2):68–75
105. Marcacci M, Zaffagnini S, Giordano G, Iacono F, Presti ML (2009) Anterior cruciate ligament reconstruction associated with extra-articular tenodesis: a prospective clinical and radiographic evaluation with 10- to 13-year follow-up. Am J Sports Med 37(4):707–714. doi:10.1177/0363546508328114
106. Ait Si Selmi T, Fabié F, Massouh T, Pourcher G, Adeleine P, Neyret P (2002) Greffe du LCA au Tendon Rotulien Sous Arthroscopie Avec ou Sans Plastie Antero-Externe. In: Chambat P, Neyret P, Deschamps G, (eds) Le Genou Du Sportif-10èmes Journées Lyonnaises De Genou. Vol Sauramps Medical; pp 221–224

107. Acquitter Y, Hulet C, Locker B, Delbarre JC, Jambou S, Vielpeau C (2003) Intérêt d'une plastie extra-articulaire dans le traitement des laxités antérieures chroniques du genou par une autogreffe de tendon rotulien. Rev Chir Orthop Reparatrice Appar Mot 89(5):413–422
108. Giraud B, Besse JL, Cladiere F, Ecochard R, Moyen B, Lerat J-L (2006) Intra-articular reconstruction of the anterior cruciate ligament with and without extra-articular supplementation by quadricipital tendon plasty: seven-year follow-up. Rev Chir Orthop Reparatrice Appar Mot 92:788–797
109. Zaffagnini S, Bruni D, Russo A et al (2008) ST/G ACL reconstruction: double strand plus extra-articular sling vs double bundle, randomized study at 3-year follow-up. Scand J Med Sci Sports 18(5):573–581. doi:10.1111/j.1600-0838.2007.00697.x
110. Vadalà AP, Iorio R, de Carli A et al (2012) An extra-articular procedure improves the clinical outcome in anterior cruciate ligament reconstruction with hamstrings in female athletes. Int Orthop (SICOT) 37(2):187–192. doi:10.1007/s00264-012-1571-0
111. Trichine F, Alsaati M, Chouteau J, Moyen B, Bouzitouna M, Maza R (2014) Patellar tendon autograft reconstruction of the anterior cruciate ligament with and without lateral plasty in advanced-stage chronic laxity. A clinical, prospective, randomized, single-blind study using passive dynamic X-rays. Knee 21(1):58–65. doi:10.1016/j.knee.2013.06.001
112. Hewison CE, Tran MN, Kaniki N, Remtulla A, Bryant D, Getgood AM (2015) Lateral extra-articular tenodesis reduces rotational laxity when combined with anterior cruciate ligament reconstruction: a systematic review of the literature. Arthroscopy. doi:10.1016/j.arthro.2015.04.089
113. Rezende FC, Moraes VY, Martimbianco ALC, Luzo MV, Franciozi CES, Belloti JC (2015) Does combined intra- and extraarticular ACL reconstruction improve function and stability? A meta-analysis. Clin Orthop Relat Res 1–10. doi:10.1007/s11999-015-4285-y
114. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K (2005) Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthroscopy 21(8):948–957. doi:10.1016/j.arthro.2005.04.110
115. Lerat J-L, Moyen BL, Cladiere F, Besse JL, Abidi H (2000) Knee instability after injury to the anterior cruciate ligament Quantification of the Lachman test. J Bone Joint Surg Br 82(1):42–47
116. Musahl V, Kopf S, Rabuck S et al (2011) Rotatory knee laxity tests and the pivot shift as tools for ACL treatment algorithm. Knee Surg Sports Traumatol Arthrosc 20(4):793–800. doi:10.1007/s00167-011-1857-6
117. Trojani C, Sbihi A, Djian P et al (2010) Causes for failure of ACL reconstruction and influence of meniscectomies after revision. Knee Surg Sports Traumatol Arthrosc 19(2):196–201. doi:10.1007/s00167-010-1201-6
118. Trojani C, Beaufils P, Burdin G et al (2012) Revision ACL reconstruction: influence of a lateral tenodesis. Knee Surg Sports Traumatol Arthrosc 20(8):1565–1570. doi:10.1007/s00167-011-1765-9

Treatment of MCL Injury in Combined ACL/MCL Injury

34

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34.1 Introduction

Combined injuries of the anterior cruciate ligament (ACL) and medial collateral ligament (MCL) are the most common multi-ligament injuries of the knee [1]. A concomitant injury is present in 78 % of grade III MCL injuries [2], with the ACL being involved in 95 % of cases [2].

The extra-synovial location of the MCL, with its abundant vascular supply, provides it with a much higher healing capacity [3–6]. In most instances, nonoperative management of isolated MCL injuries is sufficient, including injuries in high-performance athletes [7]. However, this does not appear to be the case for combined injuries [8], where chronic anteroposterior, valgus, and rotatory instability can develop [9]. If certain MCL injuries are not addressed at the time of ACL reconstruction, increased stresses on the graft can lead to higher rates of failure [8, 10–13]. The increased laxity of concomitant ACL tears can lead to certain MCL tears healing with lower biomechanical strength [14].

In particular, the treatment of an associated grade III MCL tear is the subject of much debate [6, 12, 15, 16]. In-depth evaluations of injury patterns, biomechanics, and anatomical repair techniques have shown a wider spectrum of medial and posteromedial corner structures that impart valgus and rotational stability to the knee [17–21]. This realization has challenged the traditional conservative management strategies of combined injuries, justifying a more aggressive surgical approach in certain situations [5, 15, 18, 22].

Proponents exist for isolated MCL repair or reconstruction [12, 16, 23] versus more complex MCL and posterior oblique ligament (POL) reconstructions (anatomic and nonanatomic) [18, 24–26]. Many questions still remain about the timing of surgery, as well as the best methods for fixation and graft tensioning [5, 27–30]. These factors remain important areas for basic science and clinical investigation.

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34.2 History and Physical Examination

The common factor of combined injuries is likely to be a combination of valgus, external rotation, and hyperextension [31–33]. Patients either present with pain and swelling (<3 weeks) or instability (>3 weeks). To compensate for medial instability, the patient may walk with a vaulting gait and, if swollen, with a slightly flexed knee [34, 35]. Point tenderness at the level of the proximal tibia could represent an underlying "Stener-like" lesion-guiding management toward primary repair [36]. Proximal tears are more likely to go on to heal themselves. Mid-substance tears can be mistaken for meniscal tears. Lateral meniscal tears, osteochondral fractures of the lateral femoral condyle, or lateral tibial plateau can occur in contrecoup injuries.

The American Medical Association's grading scale is most commonly used to classify the severity of MCL tears (see Table 34.1) [37]. Valgus stress testing applied at 30° of flexion remains the gold standard for assessing isolated MCL tears [38]. To improve the accuracy of clinical gapping [39], LaPrade et al. have quantified damage to individual medial structures to joint space widening seen on stress radiographs (see Table 34.2) [40].

In combined injuries, valgus stress testing at 0° of flexion is more informative [41]. Excessive laxity on valgus stress will indicate injuries to the MCL and secondary stabilizers of the knee [42]. With the anterior drawer, MCL and ACL tears together may result in greater anteroposterior (AP) translation [8, 10]. The Slocum-modified anterior drawer test is a way to identify PMC injuries. An external rotation anterior drawer test, performed in 10–15° of external rotation of the tibia, exposes PMC injuries [43]. External rotation stress is thought to be applied in the following order: PMC, anterior MCL, and ACL. Conversely, intact lateral-sided ligaments will prevent an anterior drawer of the tibia on the femur when performed in 30° of internal rotation even if the MCL and ACL are torn.

Table 34.1 American Medical Association's grading scale

American Medical Association grading scale		Clinical laxity (mm) [39]	Radiographic widening (in 20° flexion) [40]
Grade I	Localized tenderness but no instability	3–5 mm	3.2 mm difference compared to contralateral side
Grade II	Localized tenderness and a partial tear of the MCL and POL	6–10 mm	–
Grade III	Complete disruption and instability with valgus stress testing	>10 mm	9.8 mm difference compared to contralateral side

Table 34.2 Average gapping increase compared to normal knee

Protocol	Medial joint gapping (mm) in 0° knee flexion	Medial joint gapping (mm) in 20° knee flexion
Intact	7.±0.7	7.4±0.7
Proximal sMCL	9.4±1.0	10.6±1.9
MF	9.9±1.2	12.2±2.0
POL	12.2±1.5	14.1±2.1
Distal sMCL	13.2±2.6	15.3±2.3
MT	14.1±2.8	16.2±2.8
ACL	15.9±3.9	21.2±3.9
PCL	21.6±4.2	27.8±4.7

Adapted from Laprade et al. [40]

sMCL superficial medial collateral ligament, *MT* meniscotibial, *MF* meniscofemoral, *POL* posterior oblique ligament, *PCL* posterior cruciate ligament, *ACL* anterior cruciate ligament

The dial test, more commonly used to detect posterolateral corner (PLC) and PCL injuries, can also show increased external rotation at 30 and 90° of flexion with medial-sided injuries [14, 41]. Performing the examination in both the supine and prone position can be used to distinguish the difference between anteromedial and posterolateral tibial rotation, using a combination of visualization and palpation [14].

Laterally displaceable patellae and extensor mechanism damage have been variably reported in the literature to occur in 9–59 % of combined ligament injuries [44, 45]. While these injuries rarely have been found to cause instability, the literature that examines their relative contribution is poor, and careful examinations should be performed to identify potentially aggravating injuries.

34.3 Imaging

Acutely, static widening of the medial joint space on plain radiographs can indicate a medial-sided injury or structure incarceration, e.g., medial capsule or MCL (≥5 mm). The "irreducible" knee dislocation can present this way following posterolateral joint subluxation or vastus medialis entrapment [46, 47]. Valgus stress radiographs can confirm suspicions of medial-sided injury [14, 17]. LaPrade et al. quantified side-to-side differences of 1.7 mm and 3.8 mm at 0° and 20°, respectively, in isolated MCL tears and 6.5 mm and 9.8 mm at 0° and 20°, respectively, in combined MCL and posteromedial corner disruption [40]. Otherwise, an examination under anesthetic can be used to detect rotatory injuries not previously detected by preoperative imaging or examination [42].

Chronically, radiographic changes can provide clues to the pattern of underlying injury. A Pellegrini-Stieda lesion, an ossified posttraumatic avulsion lesion of the MCL from the medial epicondyle of the femur [48], a deep femoral notch sign, peaked tibial spines, or cupula lesions can indicate long-standing MCL and ACL injuries.

MRI without contrast remains the gold standard where the diagnosis of medial-sided knee injuries can be performed with an accuracy of 87 % [49]. Its greatest advantages are in suspected complete MCL tears, suspected ACL tears, persistent clinical instability, and identifying the location of tear where surgery is required [50]. Individual medial-sided structures and the exact location of the injury can be visualized (see Fig. 34.1) [51]. MRI arthrograms enhance the identification of PMC injuries. Kimori et al. found arthrography to be more useful than arthroscopy and clinical examination in detecting tears, but interpretation can be difficult [51–53].

Nakamura et al. (contributing author) developed a new classification for MCL injuries based on the appearance of the superficial medial collateral ligament (sMCL) on MRI: femoral insertion site injury (type I), tibial insertion site injury (type 2), or injury throughout the length of the MCL (type 3) [53]. All five of their type 3 injuries required MCL reconstruction and there were no type 2 injuries. No differences were observed in IKDC sagittal laxity or valgus stability in all injuries.

Ligament discontinuity, subcutaneous edema, internal (ligament) change of signal intensity, and contrecoup bipolar bone bruises have all been associated with MCL tears [54–56]. When the pivot-shift mechanism does not dissipate all the deforming forces of certain high-energy injuries, varus, the internal rotation impaction on the anteriorly subluxated proximal tibia, is thought to lead to central medial femoral condyle and posterior tibial plateau contusion [57, 58].

The recently described "wave sign" indicates a distal tibial avulsion injury (Fig. 34.2a–c) [36]. This is thought to occur because the distal end of the ligament is not tethered to other soft tissue structures locally and takes on a serpiginous appearance when it retracts proximally. Taketomi et al. described three types: an avulsion injury where the distal end of the torn ligament remains under pes anserinus, the so-called "Stener" lesion of the knee where the distal end of the ligament sits outside pes anserinus [59], and MCL incarceration within the joint. They make the argument that potentially all of these types of MCL tears require surgical intervention.

34.4 Pathoanatomy and Applied Anatomy Relating to Combined ACL/MCL Injury

LaPrade et al. have extensively described (1) bony landmarks, (2) ligaments, and (3) tendons (adductor magnus, medial head of the gastrocnemius, semimembranosus, and the pes anserinus) of the medial side of the knee [21]. The MCL complex is made of the sMCL, the deep medial collateral ligament (dMCL), and POL (part of PMC) [23]. The other constituent components of

Fig. 34.1 Coronal images of type I (**a**, **b**) and type III (**c**, **d**) MCL injuries. The superficial fiber, which is depicted as low-signal image on spin echo (**a**, *arrow*) and gradient echo (**b**, *arrow*) images, is interrupted by high-signal image at the femoral attachment site in type I MCL injury. In contrast, interruption of the superficial fiber by high-signal image is observed throughout the length of the fiber in type III MCL injury (Ref. [53])

the PMC are the semimembranosus tendon (and its multiple reflections), the oblique popliteal ligament, posterior horn of the medial meniscus, and medial joint capsule [60]. The sMCL has one femoral and two tibial attachments (proximal and distal). The femoral attachment is located 3.2 mm proximal and 4.8 mm posterior to the medial epicondyle [21]. Many reconstruction techniques incorrectly identify the medial epicondyle as the attachment site of the MCL [15, 26, 61–64]. The tibial insertion is broader, attaching primarily to soft tissues proximally and to bone distally, 60 mm from the joint line [65]. The dMCL is a vertical thickening of the medial joint capsule and consists of the MF (attaching 15.1 mm posterior and distal to the medial epicondyle) and MT ligaments (3.2 mm from medial tibial plateau) [65].

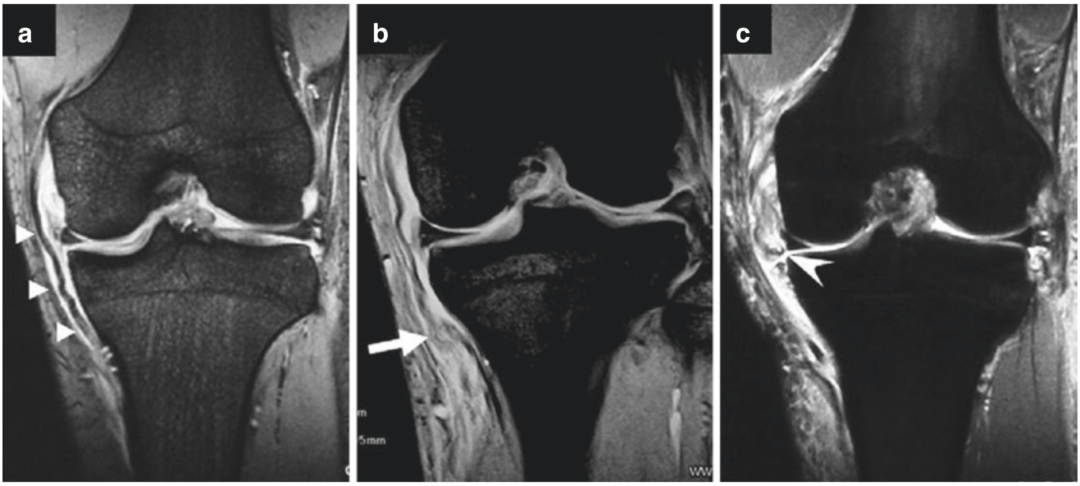

Fig. 34.2 (**a**) "Wave sign": the waving of the superficial layer (*triangle*). (**b**) The distal end of the superficial MCL (*arrow*). (**c**) The entrapment of the distal end of the superficial layer into the medial knee joint (*arrow head*) (Ref. [36])

The posterior oblique ligament (POL) arises from behind the medial femoral epicondyle, 7.7 mm distal and 6.4 mm posterior to the adductor tubercle [65]. It fans out from its origin with three fascial arms: superficial, central, and capsular [21, 61]. The central arm is the largest, inserting near the margin of the tibial articular surface, the capsular arm reinforces the PM joint capsule, and the superficial arm blends with semimembranosus.

The MCL complex is a primary restraint to direct valgus stress. It also secondarily contributes to external rotation and anteroposterior stability [23]. The sMCL provides the majority of this stability in all degrees of flexion; the dMCL only providing secondary stability. The distal division of the sMCL is a primary stabilizer for external rotation and the POL, the primary stabilizer for internal rotation, highlighting its importance in counteracting AMRI [41].

The PMC provides one third of the restraint to valgus stress in full extension, slackening off in flexion [66]. It has a secondary role in the prevention of posterior translation of the tibia. However, in the context of combined injuries, it has a more important role in the resistance to external rotation. When damage to the PMC is combined with an MCL tear, external rotation is increased by 30° [42]. Failing to address the rotational component of this injury is what is thought to lead to residual laxity and functional compromise and the main source of controversy surrounding repair or reconstruction techniques.

Pes anserinus tendons and semimembranosus have a role in tightening medial structures in external rotation and flexion. In the context of damage to medial structures, utilization of these tendons to reconstruct MCL or POL may compromise the results of surgery inadvertently. Avoiding the harvest of hamstring autograft may be preferable, instead of favoring other graft options in these cases.

34.5 Treatment

ACL reconstruction and nonsurgical treatment of grade I and II MCL injuries have outcomes similar to that of isolated ACL injury reconstructions [67, 68]. Based on this, many authors propose protection of the MCL with a knee brace and delaying ACL reconstruction surgery [1, 69, 70]. Usually a period of 6–8 weeks is required for MCL injuries to heal.

The abovementioned approach can be utilized with grade III MCL injuries even among professional athletes with successful results [7]. However, the persistent valgus and/or AMRI of certain MCL tears can compromise ACL reconstructions if the medial side is not addressed [8, 11–13].

Both of these situations of compromised stability can prevent athletes from returning to pivoting sports [1, 2, 17].

34.5.1 Nonoperative Management of MCL Injuries

The indications for the nonoperative management of both ACL and grade III MCL tears are rare [71], with very little published on the topic [72, 73]. A higher rate of instability and a lower rate of return to sport make this a less desirable option. A number of studies have evaluated the nonoperative treatment of grade III MCL tears with concurrent reconstruction of the ACL [3, 28–30, 74–76]. Halinen et al. found that nonoperative MCL management regained ROM and quadriceps strength faster [28]. Petersen and Laprell compared early and late ACL reconstruction and reported significantly higher reoperation rates for stiffness and lower Lysholm scores with early ACL reconstruction [30]. Nonoperative management of MCL injuries is not as much of an issue as early ACL reconstruction. The vast majority of surgeons prefer not to operate in the acute phase for this reason [68, 76]. However, these studies also do not confirm superiority of nonoperative MCL management. Although sagittal and valgus stability is generally restored [3, 28–30], regaining ROM can still be an issue [28, 30, 74, 76].

Many authors have recommended a “wait and see” approach [1, 2, 33, 69, 77], bracing patients to resist coronal plain movement while permitting weight bearing and ROM for 6–8 weeks [1, 17, 78, 79]. At the time of ACL reconstruction, radiography can be used for an examination under anesthesia and valgus stress views obtained on the table [53]. Residual valgus instability after ACL reconstruction, illustrated by the medial joint space opening up more than 7–10 mm in 30° of flexion compared to the other side, should be an indication to proceed onto MCL reconstruction [33, 53, 69]. Significant residual instability can also be confirmed with arthroscopic valgus stress testing. Eight to 10 mm of opening of the medial compartment suggests persistent instability.

34.5.2 Operative Management of MCL Injuries

34.5.2.1 MCL Repair

Different treatment combinations reflect changing trends in management over time [1, 17–19]. Opinion has shifted from early repair of the MCL and reconstruction of the ACL to delayed reconstruction of both ligaments when needed [1, 27, 33, 77].

Proponents of MCL repair report relatively good correction of valgus laxity with the advantage of avoiding complicated reconstruction options [68, 80–82]. Many reconstruction options are nonanatomic and only address the anterior portion of the superficial MCL [25, 26, 63]. Surgery in the acute phase is facilitated by more pliable tissue and more easily identifiable anatomical structures [25, 26]. The trade-off is a reduction in range of motion and possibly rotatory stability. Postoperative stiffness has proven to be a problem with early surgery, with 19–38 % MUA rates [28, 30, 68, 70, 76, 81–83]. Older rehabilitation protocols have been suggested as a possible cause for these findings.

Doubt has also been cast over the rotational stability of MCL repairs [63]. A recent study by Dong et al. looked at a triangular-vector reconstruction technique versus an anatomic repair technique of the MCL (See Fig. 34.3a–c) [63]. Both treatment methods effectively treated valgus instability, but medial pain and rotational instability were higher in the repair group. Repaired oblique fibers of the middle of the MCL and POL were not able to restore the medial structures to their original level of function [12, 84].

Although MCL repair in the acute phase is not typically offered, severe valgus alignment, large bony avulsions, and sMCL tibial avulsions that get incarcerated in the joint or displaced to the other side of the pes anserine tendons (“Stener-like” lesion of the knee) are all indications for acute MCL repair [33]. Although there is no high-level evidence to support the acute fixation of these lesions, much like the Stener lesion of the thumb, it is unlikely that the distally avulsed end of the sMCL will heal to its anatomic footprint if there is interposition of the sartorius fascia and hamstring tendons [59, 68].

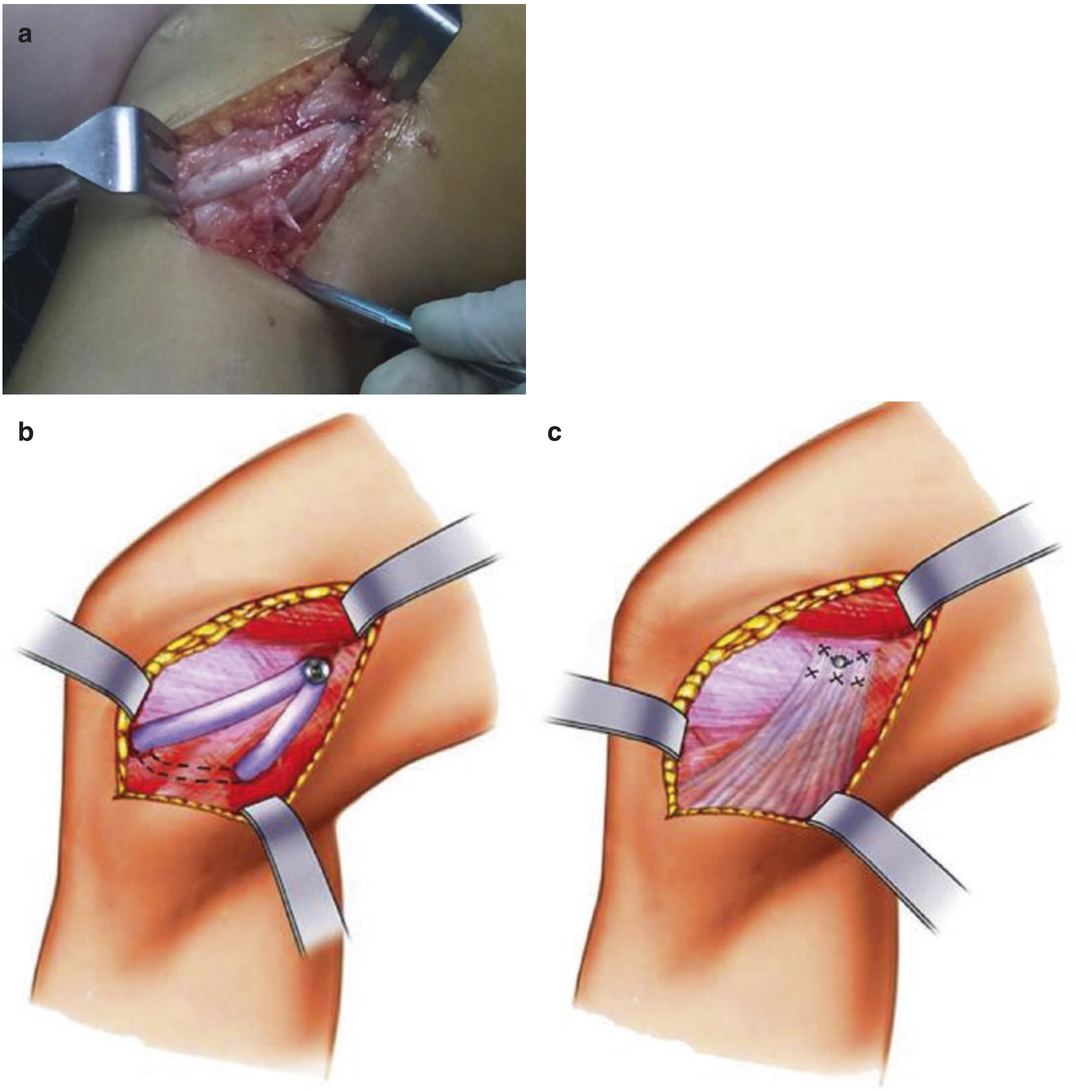

Fig. 34.3 (**a**) Photograph of triangular reconstruction technique. (**b**) Illustration of same technique. (**c**) Illustration of MCL repair using suture anchors (Ref. [24])

Our preferred approach for repair is through a medial-sided 4 cm incision centered over the medial femoral epicondyle down to the crural fascia. Under fluoroscopic control, the isometric point of the proximal sMCL insertion is found as described by Wijdicks et al. [20]. The injured structures are repaired from the deepest structures outward. A peripheral tear of the medial meniscus is commonly seen (33 %) and repaired with an open technique. An MF ligament tear can be directly repaired using sutures alone or suture anchors. Suture anchor fixation is preferred for MT ligament tears.

For proximal avulsions of the sMCL, its attachment site is found and a 3.2 mm drill is inserted to a depth of approximately 35–40 mm. The MCL is prepared with a modified running locking stitch up each side. A small slit is then made proximally, and a 4.5 mm screw with a soft tissue spiked washer is placed through the slit (see Fig. 34.4) [85]. Sutures from the free end are also tied around the screw. Final tensioning is

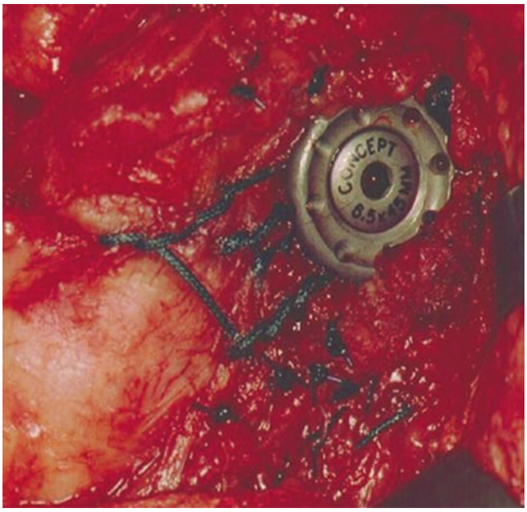

Fig. 34.4 An MCL repair using the suture post and ligament washer construct [85]

performed with the leg in about 20–30° of flexion and slight varus.

Distal sMCL avulsions can be approached through an anteromedial incision midway between the PM border of the tibia and the tibial tubercle. The sartorius expansion is incised over the top of the pes tendons and the tendons retracted distally. Most distal avulsions occur distal to the level of the pes tendons. The sMCL can be retracted proximally some distance. Two anchors are used to reattach the proximal sMCL 1 cm below the joint line. These sutures are then weaved through the proximal MCL fibers but not tied. Then similar to the proximal MCL attachment, after lock stitching the distal ligament is split and the limbs tied around and secured by a screw and washer construct [86]. Tensioning is performed with the leg in about 20–30° of flexion and slight varus. Once the distal avulsion has been repaired, the leg is placed in full extension and the proximal anchors are sutured securely.

Whelan et al. (senior author) recently showed the biomechanical reliability of a "double row" repair of distal sMCL avulsion injuries (suture-bridge repair technique) [87]. Double row repair, in the shoulder, has shown greater healing and lower re-rupture rates, encouraging its application in the knee [88, 89]. Double-loaded suture anchors are placed at the proximal aspect of the sMCL anatomic insertion on the tibia and passed through the ligament tissue and tied but not cut. "Press fit" suture anchors are then placed at the distal aspect of the sMCL anatomic insertion site on the tibia to secure the retained sutures from the proximal anchors. The proximal sutures are "crossed over" before being secured distally as per standard suture-bridge configuration (see Fig. 34.5a, b).

If required, posteromedial structures can be tightened to improve resistance to AMRI. Two methods have been described by Jackson et al. [90]. The first of these is based on a technique described by Hughston et al. [91]. Laxity is removed by increasing the distance between the origin and insertion of the lax structure. The Lax segments are attached to surrounding intact structures, increasing the distance the ligament or tendon travels, increasing its tension. This is then followed by mattress stitch imbrication of the body of the structure. Alternatively, the posterior medial capsule can be released from the meniscus and re-sutured to it in a more advanced position in a "pants-over-vest" fashion. Both of these procedures are best performed with the patient supine, the hip in external rotation, and the knee positioned in 30° of flexion, internally rotated and under gentle varus stress.

34.5.2.2 MCL Reconstruction

Chronic valgus laxity resulting in symptomatic instability unresponsive to conservative treatment is an indication for MCL reconstruction [17, 69]. Abnormal shear stresses and load patterns in an unstable knee can lead to degenerative change [92]. To avoid this, addressing all injured medial knee structures by restoration of native anatomy and insertion sites are recommended [17–19, 93]. Reconstruction techniques differ in graft choice, fixation method, tensioning method, number of bundles, and the medial structures they aim to reconstruct. No true consensus on the optimal method of reconstruction exists at the current time.

Reconstruction techniques can be split into three categories: anatomic, nonanatomic, and nonanatomic tendon transfer reconstructions [77]. LaPrade et al. described an anatomical reconstruction

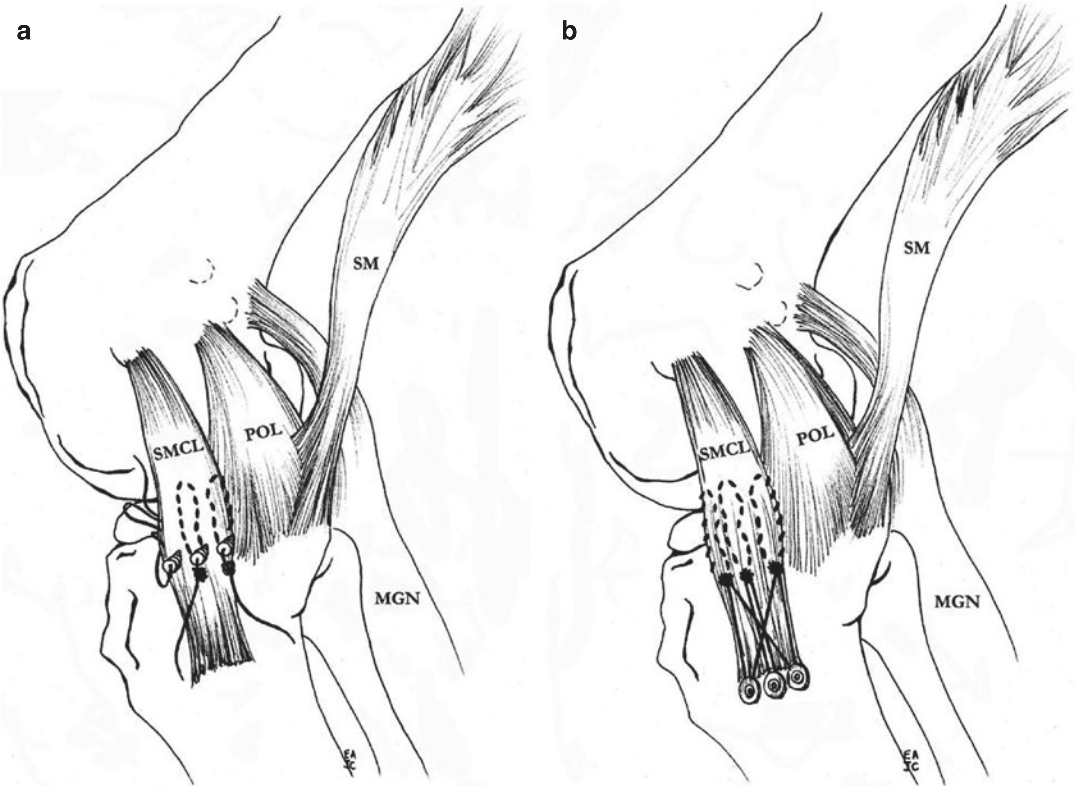

Fig. 34.5 (**a**) sMCL suture-bridge repair technique. Double-loaded suture anchors are placed at the proximal aspect of the sMCL anatomic insertion on the tibia, and the sutures are passed through the ligament tissue and tied but not cut. (**b**) "Press fit" suture anchors placed at the distal aspect of the sMCL anatomic insertion on the tibia to secure the retained sutures from the proximal anchors. The proximal sutures are "crossed over" before being secured distally as per standard suture-bridge configuration (Ref. [87])

of MCL and POL to their precise, native attachment sites using hamstrings double-bundle autografts (see Fig. 34.6) [18]. Medial joint space gapping was <3 mm in all 24 of their patients. Accurate restoration of anatomic attachment sites, with independent ligament tensioning, may explain these good results. However, the extensive approach and requirement for multiple tunnels add complexity to the operation. Inadvertent disruption of bone tunnels created for other ligament reconstructions can lead to graft failure of either or both ligaments. Concerns have also been raised about stress shielding and altered knee mechanics that results from significantly over-tensioned grafts [94].

Significant heterogeneity exists among nonanatomic reconstruction techniques [12, 16, 26, 63, 95–97]. Single- and quadruple-bundle hamstring autografts appear to perform equally well, with minimal medial joint gapping on valgus stress [16, 26, 95]. Tendo-Achilles (T-A) allograft is also a popular choice of graft, avoiding further compromise of medial stability through the sacrifice of hamstring autografts. Both single- and double-bundle techniques have achieved good resistance to medial gapping [12, 97]. Quadriceps tendon and bone-patella-tendon-bone techniques have also been described [16].

Dong et al.'s nonanatomic triangular-ligament reconstruction with a single-bundle semitendinosus allograft appeared to show superior control of rotatory instability compared to anatomic repair. Their graft was fixed into both ends of an anterior to posterior drilled tibial tunnel [63]. The intervening tendon is fixed at the apex of the construct in a single femoral tunnel at the level of the medial epicondyle of the femur (see Fig. 34.3).

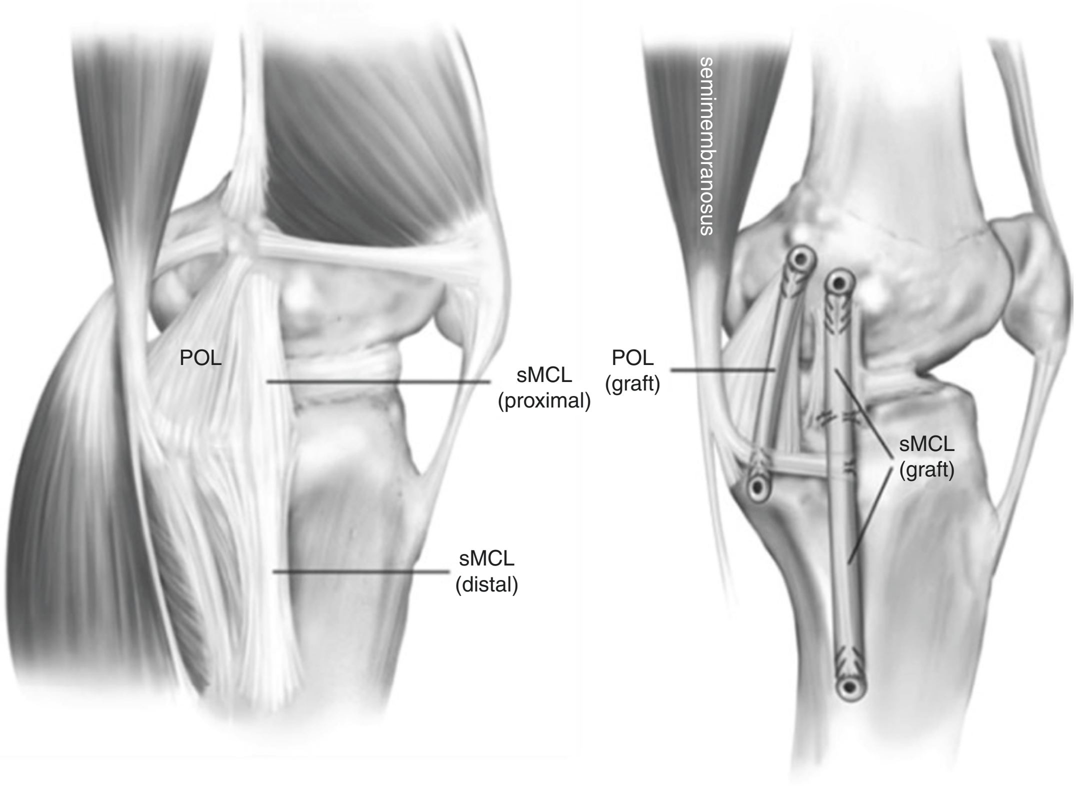

Fig. 34.6 A diagram of a right knee illustrates the superficial medial collateral ligament (*sMCL*) and posterior oblique ligament (*POL*) reconstruction grafts (Ref. [93])

Allograft, however, is not as readily available in all hospitals making this a potentially expensive option with an inherent risk of disease transmission and biomechanical compromise. Complex reconstruction techniques requiring multiple bone tunnels and points of fixation stand to interfere with tunnels needed for ACL reconstruction [97]. They also may not fully restore the functions of the sMCL and POL. A number of the abovementioned techniques use a single femoral tunnel as representative of the proximal insertion sites of the sMCL and POL, when in fact their insertion site is not the same [20, 24, 26, 64]. The medial epicondyle is often quoted as the site used for assessing isometry [61, 62]. The correct proximal femoral attachment of the sMCL is 3.2 mm proximal and 4.8 mm posterior to the medial epicondyle [20, 21].

Nonanatomic tendon transfer preserves the distal attachment of the hamstrings (see Fig. 34.7). Proximal fixation of the graft usually occurs into a single femoral tunnel in the medial femoral epicondyle, and a posterior limb replicates the POL. Variants of this last feature have been described that either interact with the semimembranosus tendon or fit into a posterior tibial tunnel [15]. This has included suturing the semitendinosus tendon to itself [5] or passing the free end of the graft posterior to anterior through a tibial tunnel [25]. Minimal differences in side-to-side joint space widening under valgus stress have been reported with the majority of these techniques. However, in Lind et al.'s study, 50 % of patients had >3 mm medial widening [25].

In tendon transfer, maintaining the insertion site of the hamstrings anteriorises the position of the reconstructed sMCL. This is thought to be biomechanically inferior [18]. These techniques also use a single femoral insertion point to represent sMCL and POL.

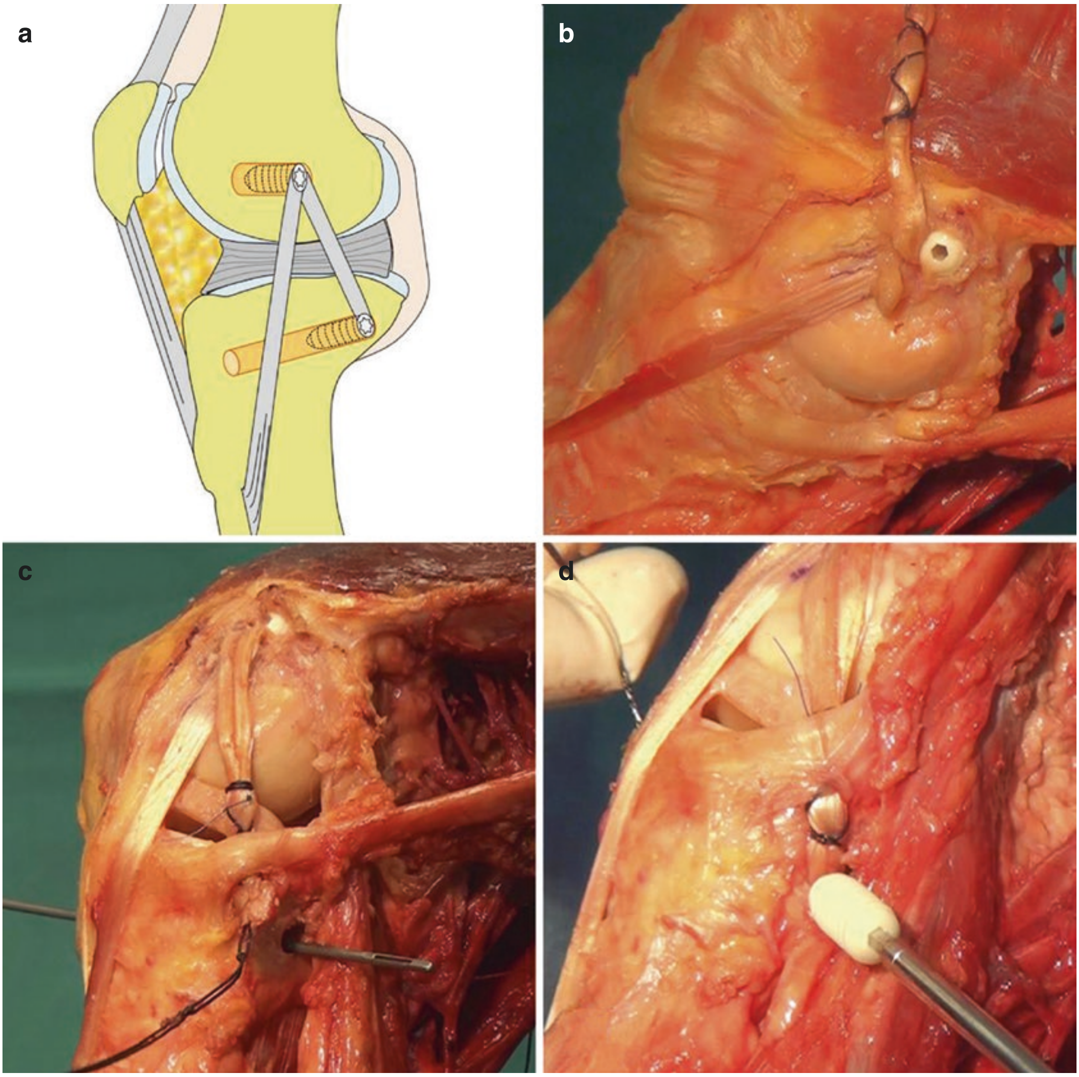

Fig. 34.7 (**a**) Illustration of Lind's technique. (**b**) The tendon loop is armed in a baseball suture fashion, passed into the tunnel, and fixed with an interference screw. (**c**, **d**) The free end of the graft is passed through the posterior tibial tunnel opening and fixed here with an interference screw [33]

Our preferred technique is tendon transfer using hamstring autografts. The distal insertions of these tendons are left intact, but the tendons are rerouted around a 4.5 mm screw suture post and ligament washer construct at the distal anatomical footprint of the sMCL. The exact location of the distal footprint and proximal insertion point is determined by the technique described by LaPrade et al. [20]. A 25 mm femoral tunnel is created. The graft is cut to the appropriate length and a whipstitch run along the free end of both tendons. Using a beath pin, the sutures from the free end of the graft are passed through the femur at the anatomical insertion site of the sMCL and out through the skin on the lateral side, pulling the graft along with it into the tunnel. The ACL is usually fixed at this stage (often using BTB autograft) in full extension. The MCL is tensioned in 30° with a slight varus moment (slight "figure-of-four" position) and fixed with a biocomposite interference screw. We also then often back the fixation up by tying the sutures over a button on the lateral side of the femur.

If allograft is required or desired for a particular patient, we prefer the nonanatomic reconstruction of the sMCL described by Marx et al. [97]. The three-point sMCL fixation principle described by LaPrade et al. is used for fixation: the proximal isometric insertion site in the femur just proximal and posterior to the medial epicondyle (T-A bone plug with interference screw), the proximal tibia 1.5 cm below the joint line (with suture anchors), and distal to the pes tendons 6 cm distal to the joint line [20, 21]. The proximal suture anchors are tied with the knee in full extension. A suture post and ligament washer construct, as previously described, using a large 3.5-mm bicortical screw and 18-mm spiked washer is used for distal fixation.

34.5.2.3 Graft Tensioning

Correct tensioning of ligaments in reconstruction is dependent on choosing the correct location of ligament insertion, understanding the mechanical properties of the graft, the chosen fixation, and tensioning method [98]. On the basis of Wijdicks et al.'s study, the sMCL is the primary restraint to valgus stress throughout the full range of knee flexion [19]. The distal portion of the sMCL primarily resists external rotation with increasing knee flexion. The ACL is tensioned and fixed first before the medial structures are fixed [99]. Most techniques describe tensioning the sMCL in 30° of flexion and varus [15, 26, 93, 100, 101].

The POL, on the other hand, has been shown to be most important in counteracting valgus stress and internal rotation in full extension [19]. There does not appear to be one consistent trend in the way the POL is tensioned, with variations in position of flexion, internal rotation, and presence or absence of varus stress. Recent recommendations have suggested tensioning in full extension to avoid over-constraint of the posteromedial capsule [12, 93].

34.5.3 Postoperative Rehabilitation

In the context of combined injuries, ACL rehabilitation takes precedence over medial-sided repair [78]. The general goal of prehabilitation is to allow sufficient healing of medial structures, restoration of ROM, quadriceps strength, and reduction in swelling before proceeding to an ACL reconstruction within 5–7 weeks after injury [14, 17].

A hinged brace is useful at this stage to control valgus and rotational stress. Weight bearing, ROM, and eccentric quadriceps and hamstrings strengthening exercises are encouraged as early as comfort allows. The ROM achieved on a stationary exercise bike is thought to provide the same stimulus for healing as the use of a constant passive motion machine in animals, accelerating the healing of grade III MCL tears [14]. Side-to-side exercises and activities should be avoided to prevent applying any unnecessary stresses on the collaterals [17].

Our postoperative rehabilitation protocol is performed as described by LaPrade et al. [14]. After surgery, ACL rehabilitation takes precedence over medial-sided repair [78]. ROM exercises are initiated within the "safe zone" determined intraoperatively, the range that does not put excessive strain on the MCL repair or reconstruction. Ideally, we aim for a passive or passive-assisted ROM from 0° to 90° immediately after surgery to minimize the risk of arthrofibrosis. If a bone-tendon-bone (B-T-B) autograft has been used, we do not permit our patients to weight bear for the first 2 weeks. Aggressive patella-femoral mobilization, quadriceps reactivation, straight leg raises in the knee brace, and hip extension and abduction exercises are encouraged immediately after surgery.

After 2–4 weeks range of motion is increased as tolerated with a target of 0–130° by 6 weeks. This rehabilitation is performed with the knee in a hinged brace. Progression to weight bearing as tolerated is likely to be between 2 and 6 weeks postoperatively when a normal gait without immobilizer or crutches has been achieved. It is important for the patient to be able to ambulate without effusions developing as this can affect both ROM and quadriceps strength.

At 6 weeks when good quadriceps control can be demonstrated, the hinged brace is discontinued. Closed chain exercises can be instituted alongside stationary bike usage with light resis-

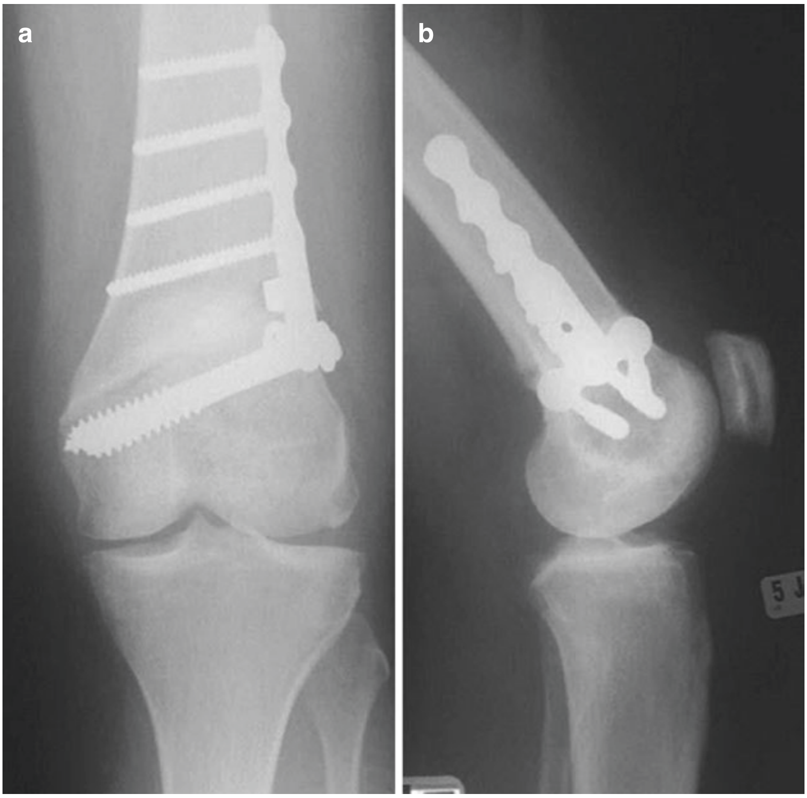

Fig. 34.8 Distal femoral osteotomy used to correct valgus malalignment, taken 8 months postoperatively (Ref. [109]). (**a**) anteroposterior plain radiograph view of distal femoral osteotomy plating. (**b**) Lateral plain radiograph view of distal femoral osteotomy plating

tance. Hamstring curls and double-leg presses to a maximum of 70° knee flexion are also permitted but no open chain exercises at this stage.

Over the next 8–10 weeks, the patient will progress through a number of strength, motion, and balance exercises, consistent with the standard goal-based rehabilitation of an ACL reconstruction. Prior to a return to full sporting activities, the patient should have a full ROM, no instability, muscle strength that measures 85 % of the contralateral side, satisfactory proprioceptive ability, no MCL tenderness, and no effusion [78]. Consideration should be paid to the usage of knee bracing during sport if required.

34.5.4 Role of Osteotomy

Long-standing knee instability adds an additional degree of complexity to ligament reconstruction surgery. It can be accompanied by bony abnormalities and joint degeneration caused by joints that drift into either excessive varus or valgus over time [102]. An additional high tibial osteotomy (HTO) combined with soft tissue reconstruction can often mean the difference between success and failure in cases like these [103, 104].

The larger proportion of the literature on this topic exists for genu varum or hyperextension and varus thrust where HTO has been shown to halt the progression of arthritis in the medium term [103, 105–107]. Comparatively, very little has been written on the use of HTO to correct valgus malalignment that may be the result of medial-sided soft tissue injuries. Nevertheless, varus osteotomies are an option in the setting of chronic medial-sided laxity and valgus malalignment (see Fig. 34.8) [108]. HTO or distal femoral osteotomies (DFO-lateral opening wedge or medial closing wedge) may be performed for a weight-bearing line that falls lateral to the lateral tibial spine in the lateral compartment and beyond or a mechanical axis of 10° valgus. Due to the concern of joint obliquity of varus-producing HTOs, a DFO is often utilized [109].

Very few reports exist on the use of varus osteotomy to address ligamentous laxity. Cameron and Saha treated 37 patients with chronic MCL instability with distal femoral osteotomy [110]. An improvement in gait pattern was observed in 34 patients. Although laxity in the MCL remained even after osteotomy, this did not result in a functional deficit in being able to conduct daily activities. Phisitkul et al. described a similar experience where they felt in active patients or athletes that a second-stage procedure to reconstruct the ligaments was often required to address residual laxity [109].

34.6 Summary

High-level evidence does not exist in the literature to instruct us on how to manage combined injuries of the ACL and MCL. However, there appears to be no benefit to the repair or reconstruction of the MCL and ACL in the acute phase. From our own experience, we have seen that acutely presenting grade III MCL injuries often heal after 4–6 weeks of protection or at worst have residual grade II laxity that does not require operative attention. A "Stener lesion of the knee" (ligament tear from its tibial insertion) is an indication for acute MCL repair. A "wait and see" approach is the preferred strategy taken by the vast majority of surgeons. If valgus instability is present after ACL reconstruction, MCL reconstruction is indicated using allograft or autograft. A superficial MCL reconstruction or a superficial MCL plus posterior oblique ligament (POL) reconstruction technique can be used. Clinically, both techniques provide equally good results. Important technical points to all reconstructions include anatomic tunnel placement at the femur and tibial insertions and fixing the superficial MCL graft at 30° of flexion with varus stress.

References

1. Grant JA et al (2012) Treatment of combined complete tears of the anterior cruciate and medial collateral ligaments. Arthroscopy 28(1):110–122
2. Kovachevich R et al (2009) Operative management of the medial collateral ligament in the multi-ligament injured knee: an evidence-based systematic review. Knee Surg Sports Traumatol Arthrosc 17(7): 823–829
3. Halinen J et al (2006) Operative and nonoperative treatments of medial collateral ligament rupture with early anterior cruciate ligament reconstruction: a prospective randomized study. Am J Sports Med 34(7):1134–1140
4. Hara K et al (2008) Isolated anterior cruciate ligament reconstruction in patients with chronic anterior cruciate ligament insufficiency combined with grade II valgus laxity. Am J Sports Med 36(2):333–339
5. Stannard JP et al (2012) Posteromedial corner injury in knee dislocations. J Knee Surg 25(5):429–434
6. Kannus P, Jarvinen M (1988) Osteoarthrosis in a knee joint due to chronic posttraumatic insufficiency of the medial collateral ligament. Nine-year follow-up. Clin Rheumatol 7(2):200–207
7. Indelicato PA, Hermansdorfer J, Huegel M (1990) Nonoperative management of complete tears of the medial collateral ligament of the knee in intercollegiate football players. Clin Orthop Relat Res 256:174–177
8. Zaffagnini S et al (2011) Does chronic medial collateral ligament laxity influence the outcome of anterior cruciate ligament reconstruction?: a prospective evaluation with a minimum three-year follow-up. J Bone Joint Surg Br 93(8):1060–1064
9. Kurimura M et al (2004) Factors for the presence of anteromedial rotatory instability of the knee. J Orthop Sci 9(4):380–385
10. Haimes JL et al (1994) Role of the medial structures in the intact and anterior cruciate ligament-deficient knee. Limits of motion in the human knee. Am J Sports Med 22(3):402–409
11. Battaglia MJ 2nd et al (2009) Medial collateral ligament injuries and subsequent load on the anterior cruciate ligament: a biomechanical evaluation in a cadaveric model. Am J Sports Med 37(2):305–311
12. Liu X et al (2013) Surgical treatment of subacute and chronic valgus instability in multiligament-injured knees with superficial medial collateral ligament reconstruction using Achilles allografts: a quantitative analysis with a minimum 2-year follow-up. Am J Sports Med 41(5):1044–1050
13. Woo SL et al (1987) Treatment of the medial collateral ligament injury. II: structure and function of canine knees in response to differing treatment regimens. Am J Sports Med 15(1):22–29
14. Laprade RF, Wijdicks CA (2012) The management of injuries to the medial side of the knee. J Orthop Sports Phys Ther 42(3):221–233
15. Kim SJ et al (2008) Concomitant reconstruction of the medial collateral and posterior oblique ligaments for medial instability of the knee. J Bone Joint Surg Br 90(10):1323–1327
16. Koga H et al (2012) Surgical management of grade 3 medial knee injuries combined with cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc 20(1):88–94

17. Wijdicks CA et al (2010) Injuries to the medial collateral ligament and associated medial structures of the knee. J Bone Joint Surg Am 92(5):1266–1280
18. Laprade RF, Wijdicks CA (2012) Surgical technique: development of an anatomic medial knee reconstruction. Clin Orthop Relat Res 470(3):806–814
19. Wijdicks CA et al (2009) Medial knee injury: part 2, load sharing between the posterior oblique ligament and superficial medial collateral ligament. Am J Sports Med 37(9):1771–1776
20. Wijdicks CA et al (2009) Radiographic identification of the primary medial knee structures. J Bone Joint Surg Am 91(3):521–529
21. LaPrade RF et al (2007) The anatomy of the medial part of the knee. J Bone Joint Surg Am 89(9):2000–2010
22. Fanelli GC, Harris JD (2006) Surgical treatment of acute medial collateral ligament and posteromedial corner injuries of the knee. Sports Med Arthrosc 14(2):78–83
23. Marchant MH Jr et al (2011) Management of medial-sided knee injuries, part 1: medial collateral ligament. Am J Sports Med 39(5):1102–1113
24. Dong JT et al (2012) Application of triangular vector to functionally reconstruct the medial collateral ligament with double-bundle allograft technique. Arthroscopy 28(10):1445–1453
25. Lind M et al (2009) Anatomical reconstruction of the medial collateral ligament and posteromedial corner of the knee in patients with chronic medial collateral ligament instability. Am J Sports Med 37(6):1116–1122
26. Yoshiya S et al (2005) Medial collateral ligament reconstruction using autogenous hamstring tendons: technique and results in initial cases. Am J Sports Med 33(9):1380–1385
27. DeLong JM, Waterman BR (2015) Surgical repair of medial collateral ligament and posteromedial corner injuries of the knee: a systematic review. Arthroscopy 31:2249–2255
28. Halinen J, Lindahl J, Hirvensalo E (2009) Range of motion and quadriceps muscle power after early surgical treatment of acute combined anterior cruciate and grade-III medial collateral ligament injuries. A prospective randomized study. J Bone Joint Surg Am 91(6):1305–1312
29. Millett PJ et al (2004) Early ACL reconstruction in combined ACL-MCL injuries. J Knee Surg 17(2):94–98
30. Petersen W, Laprell H (1999) Combined injuries of the medial collateral ligament and the anterior cruciate ligament. Early ACL reconstruction versus late ACL reconstruction. Arch Orthop Trauma Surg 119(5–6):258–262
31. Schenck RC (2003) Classification of knee dislocations. Oper Tech Sports Med 11(3):193–198
32. Peterson L et al (2000) Incidence of football injuries and complaints in different age groups and skill-level groups. Am J Sports Med 28(5 Suppl):S51–S57
33. Bonasia DE et al (2012) Treatment of medial and posteromedial knee instability: indications, techniques, and review of the results. Iowa Orthop J 32:173–183
34. Hughston JC et al (1976) Classification of knee ligament instabilities. Part I. The medial compartment and cruciate ligaments. J Bone Joint Surg Am 58(2):159–172
35. Hughston JC et al (1976) Classification of knee ligament instabilities. Part II. The lateral compartment. J Bone Joint Surg Am 58(2):173–179
36. Taketomi S et al (2014) Clinical features and injury patterns of medial collateral ligament tibial side avulsions: “wave sign” on magnetic resonance imaging is essential for diagnosis. Knee 21(6):1151–1155
37. Association., A.M., Committee on the Medical Aspects of Sports (1966) Standard nomenclature of athletic injuries. American Medical Association, Chicago, pp 99–100
38. Grood ES et al (1981) Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. J Bone Joint Surg Am 63(8):1257–1269
39. Phisitkul P et al (2006) MCL injuries of the knee: current concepts review. Iowa Orthop J 26:77–90
40. Laprade RF et al (2010) Correlation of valgus stress radiographs with medial knee ligament injuries: an in vitro biomechanical study. Am J Sports Med 38(2):330–338
41. Griffith CJ et al (2009) Medial knee injury: part 1, static function of the individual components of the main medial knee structures. Am J Sports Med 37(9):1762–1770
42. Norwood LA Jr, Hughston JC (1980) Combined anterolateral-anteromedial rotatory instability of the knee. Clin Orthop Relat Res 147:62–67
43. Slocum DB, Larson RL (2007) Rotatory instability of the knee: its pathogenesis and a clinical test to demonstrate its presence. 1968. Clin Orthop Relat Res 454:5–13, discussion 3–4
44. Hunter SC, Marascalco R, Hughston JC (1983) Disruption of the vastus medialis obliquus with medial knee ligament injuries. Am J Sports Med 11(6):427–431
45. Allen BJ et al (2015) Medial patellofemoral ligament tears in the setting of multiligament knee injuries rarely cause patellar instability. Am J Sports Med 43(6):1386–1390
46. Silverberg DA, Acus R (2004) Irreducible posterolateral knee dislocation associated with interposition of the vastus medialis. Am J Sports Med 32(5):1313–1316
47. Patel JJ (1999) Intra-articular entrapment of the medial collateral ligament: radiographic and MRI findings. Skeletal Radiol 28(11):658–660
48. Hunter TB, Peltier LF, Lund PJ (2000) Radiologic history exhibit. Musculoskeletal eponyms: who are those guys? Radiographics 20(3):819–836
49. Yao L, Dungan D, Seeger LL (1994) MR imaging of tibial collateral ligament injury: comparison with clinical examination. Skeletal Radiol 23(7): 521–524

50. Indelicato PA, Linton R (2003) Medial ligament injuries in the adult. In: Miller M (ed) DeLee and Drez's orthopaedic sports medicine: principles and practice. Elsevier Saunders, Philadelphia
51. Loredo R et al (1999) Posteromedial corner of the knee: MR imaging with gross anatomic correlation. Skeletal Radiol 28(6):305–311
52. Kimori K et al (1989) Evaluation of arthrography and arthroscopy for lesions of the posteromedial corner of the knee. Am J Sports Med 17(5):638–643
53. Nakamura N et al (2003) Acute grade III medial collateral ligament injury of the knee associated with anterior cruciate ligament tear. The usefulness of magnetic resonance imaging in determining a treatment regimen. Am J Sports Med 31(2):261–267
54. Miller MD et al (1998) The natural history of bone bruises. A prospective study of magnetic resonance imaging-detected trabecular microfractures in patients with isolated medial collateral ligament injuries. Am J Sports Med 26(1):15–19
55. Schweitzer ME et al (1995) Medial collateral ligament injuries: evaluation of multiple signs, prevalence and location of associated bone bruises, and assessment with MR imaging. Radiology 194(3):825–829
56. Sanders TG et al (2000) Bone contusion patterns of the knee at MR imaging: footprint of the mechanism of injury. Radiographics 20(Spec No):S135–S151
57. Kaplan PA et al (1999) Bone contusions of the posterior lip of the medial tibial plateau (contrecoup injury) and associated internal derangements of the knee at MR imaging. Radiology 211(3):747–753
58. Yoon KH, Yoo JH, Kim KI (2011) Bone contusion and associated meniscal and medial collateral ligament injury in patients with anterior cruciate ligament rupture. J Bone Joint Surg Am 93(16):1510–1518
59. Corten K et al (2010) Case reports: a stener-like lesion of the medial collateral ligament of the knee. Clin Orthop Relat Res 468(1):289–293
60. Tibor LM et al (2011) Management of medial-sided knee injuries, part 2: posteromedial corner. Am J Sports Med 39(6):1332–1340
61. Sims WF, Jacobson KE (2004) The posteromedial corner of the knee: medial-sided injury patterns revisited. Am J Sports Med 32(2):337–345
62. Warren LF, Marshall JL (1979) The supporting structures and layers on the medial side of the knee: an anatomical analysis. J Bone Joint Surg Am 61(1):56–62
63. Dong J et al (2015) Surgical treatment of acute grade III medial collateral ligament injury combined with anterior cruciate ligament injury: anatomic ligament repair versus triangular ligament reconstruction. Arthroscopy 31(6):1108–1116
64. Weimann A et al (2012) Reconstruction of the posterior oblique ligament and the posterior cruciate ligament in knees with posteromedial instability. Arthroscopy 28(9):1283–1289
65. Wijdicks CA et al (2010) Structural properties of the primary medial knee ligaments. Am J Sports Med 38(8):1638–1646
66. Robinson JR et al (2004) The posteromedial corner revisited. An anatomical description of the passive restraining structures of the medial aspect of the human knee. J Bone Joint Surg Br 86(5):674–681
67. Edson CJ (2006) Conservative and postoperative rehabilitation of isolated and combined injuries of the medial collateral ligament. Sports Med Arthrosc 14(2):105–110
68. Robins AJ, Newman AP, Burks RT (1993) Postoperative return of motion in anterior cruciate ligament and medial collateral ligament injuries. The effect of medial collateral ligament rupture location. Am J Sports Med 21(1):20–25
69. Miyamoto RG, Bosco JA, Sherman OH (2009) Treatment of medial collateral ligament injuries. J Am Acad Orthop Surg 17(3):152–161
70. Magit D et al (2007) Arthrofibrosis of the knee. J Am Acad Orthop Surg 15(11):682–694
71. Edwards GA, Sarasin SM, Davies AP (2013) Dislocation of the knee: an epidemic in waiting? J Emerg Med 44(1):68–71
72. Jokl P et al (1984) Non-operative treatment of severe injuries to the medial and anterior cruciate ligaments of the knee. J Bone Joint Surg Am 66(5):741–744
73. Sandberg R et al (1987) Operative versus non-operative treatment of recent injuries to the ligaments of the knee. A prospective randomized study. J Bone Joint Surg Am 69(8):1120–1126
74. Ballmer PM, Ballmer FT, Jakob RP (1991) Reconstruction of the anterior cruciate ligament alone in the treatment of a combined instability with complete rupture of the medial collateral ligament. A prospective study. Arch Orthop Trauma Surg 110(3):139–141
75. Sankar WN et al (2006) Combined anterior cruciate ligament and medial collateral ligament injuries in adolescents. J Pediatr Orthop 26(6):733–736
76. Shelbourne KD, Porter DA (1992) Anterior cruciate ligament-medial collateral ligament injury: nonoperative management of medial collateral ligament tears with anterior cruciate ligament reconstruction. A preliminary report. Am J Sports Med 20(3):283–286
77. DeLong JM, Waterman BR (2015) Surgical techniques for the reconstruction of medial collateral ligament and posteromedial corner injuries of the knee: a systematic review. Arthroscopy 31:2258–72.e1
78. Wilson BF (2015) Medial collateral ligament and posterior medial corner injuries. In: Miller MD (ed) DeLee and Drez's orthopaedic sports medicine: principles and practice. Philadelphia, Elsevier, pp 1183–1194
79. Frank CB, Loitz BJ, Shrive NG (1995) Injury location affects ligament healing. A morphologic and mechanical study of the healing rabbit medial collateral ligament. Acta Orthop Scand 66(5):455–462
80. Ibrahim SA (1999) Primary repair of the cruciate and collateral ligaments after traumatic dislocation of the knee. J Bone Joint Surg Br 81(6):987–990

81. Owens BD et al (2007) Primary repair of knee dislocations: results in 25 patients (28 knees) at a mean follow-up of four years. J Orthop Trauma 21(2):92–96
82. Noyes FR, Barber-Westin SD (1995) The treatment of acute combined ruptures of the anterior cruciate and medial ligaments of the knee. Am J Sports Med 23(4):380–389
83. Andersson C, Gillquist J (1992) Treatment of acute isolated and combined ruptures of the anterior cruciate ligament. A long-term follow-up study. Am J Sports Med 20(1):7–12
84. Zantop T et al (2007) The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. Am J Sports Med 35(2):223–227
85. Levy BA, Stuart M (2012) ACL, PCL, and medial-sided injuries of the knee. In: Fsas GC (ed) The multiple ligament injured knee: a practical guide to management. Springer, New York
86. Whelan DB, Levy B (2015) Knee dislocations. In: Court-Brown CM HJ, McQueen MM, Ricci WM, Tornetta P III (eds) Rockwood and Green's fractures in adults. Wolters Kluwer Health, Philadelphia
87. Whelan D et al (2015) Double-row repair of the distal attachment of the superficial medial collateral ligament: a basic science pilot study. Knee Surg Sports Traumatol Arthrosc 23(10):2820–2824
88. DeHaan AM et al (2012) Does double-row rotator cuff repair improve functional outcome of patients compared with single-row technique? A systematic review. Am J Sports Med 40(5):1176–1185
89. Saridakis P, Jones G (2010) Outcomes of single-row and double-row arthroscopic rotator cuff repair: a systematic review. J Bone Joint Surg Am 92(3): 732–742
90. Benjamin Jackson J 3rd, Ferguson CM, Martin DF (2006) Surgical treatment of chronic posteromedial instability using capsular procedures. Sports Med Arthrosc 14(2):91–95
91. Hughston JC (2003) Knee ligaments. Injury and repair. Mosby-Year Book, St Louis, pp 149–241
92. Shapiro MS et al (1991) The effect of section of the medial collateral ligament on force generated in the anterior cruciate ligament. J Bone Joint Surg Am 73(2):248–256
93. Coobs BR et al (2010) An in vitro analysis of an anatomical medial knee reconstruction. Am J Sports Med 38(2):339–347
94. Van den Bogaerde JM et al (2011) The superficial medial collateral ligament reconstruction of the knee: effect of altering graft length on knee kinematics and stability. Knee Surg Sports Traumatol Arthrosc 19(Suppl 1):S60–S68
95. Kitamura N et al (2013) A novel medial collateral ligament reconstruction procedure using semitendinosus tendon autograft in patients with multiligamentous knee injuries: clinical outcomes. Am J Sports Med 41(6):1274–1281
96. Zhang H et al (2014) Tibial inlay reconstruction of the medial collateral ligament using Achilles tendon allograft for the treatment of medial instability of the knee. Knee Surg Sports Traumatol Arthrosc 22(2):279–284
97. Marx RG, Hetsroni I (2012) Surgical technique: medial collateral ligament reconstruction using Achilles allograft for combined knee ligament injury. Clin Orthop Relat Res 470(3):798–805
98. Sherman SL et al (2012) Graft tensioning during knee ligament reconstruction: principles and practice. J Am Acad Orthop Surg 20(10):633–645
99. Fanelli G (2015) Combined PCL, ACL, posteromedial and posterolateral reconstruction. In: Fanelli G (ed) Posterior cruciate ligament injuries: a practical guide to management. Springer, Switzerland, pp 173–188
100. Stannard JP (2010) Medial and posteromedial instability of the knee: evaluation, treatment, and results. Sports Med Arthrosc 18(4):263–268
101. Borden PS, Kantaras AT, Caborn DN (2002) Medial collateral ligament reconstruction with allograft using a double-bundle technique. Arthroscopy 18(4):E19
102. Cantin O et al (2015) The role of high tibial osteotomy in the treatment of knee laxity: a comprehensive review. Knee Surg Sports Traumatol Arthrosc 23(10):3026–3037
103. Li Y et al (2015) Clinical outcome of simultaneous high tibial osteotomy and anterior cruciate ligament reconstruction for medial compartment osteoarthritis in young patients with anterior cruciate ligament-deficient knees: a systematic review. Arthroscopy 31(3):507–519
104. Petrigliano FA et al (2012) The effect of proximal tibial slope on dynamic stability testing of the posterior cruciate ligament- and posterolateral corner-deficient knee. Am J Sports Med 40(6): 1322–1328
105. Gardiner A et al (2010) Osteotomies about the knee for tibiofemoral malalignment in the athletic patient. Am J Sports Med 38(5):1038–1047
106. Naudie DD, Amendola A, Fowler PJ (2004) Opening wedge high tibial osteotomy for symptomatic hyperextension-varus thrust. Am J Sports Med 32(1):60–70
107. Trojani C et al (2014) Anterior cruciate ligament reconstruction combined with valgus high tibial osteotomy allows return to sports. Orthop Traumatol Surg Res 100(2):209–212
108. Jiang KN, West RV (2015) Management of chronic combined ACL medial posteromedial instability of the knee. Sports Med Arthrosc 23(2):85–90
109. Phisitkul P, Wolf BR, Amendola A (2006) Role of high tibial and distal femoral osteotomies in the treatment of lateral-posterolateral and medial instabilities of the knee. Sports Med Arthrosc 14(2):96–104
110. Cameron JC, Saha S (1994) Management of medial collateral ligament laxity. Orthop Clin North Am 25(3):527–532

ACL Reconstruction in the Multiligament Knee

35

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35.1 Multiligament Injury and Patient Selection

While multiligament knee injuries are rare, failure to diagnose and treat them properly can potentially lead to devastating outcomes. These knee injuries are usually the result of high-energy trauma, and knee dislocation and other associated injuries should be considered and evaluated as such. Initial evaluation and management include detailed history and physical examination, beginning with a complete neurovascular examination including ankle-brachial index, assessment of the soft tissues, and determination of the instability pattern. Imaging should include plain radiographs, stress views if necessary, and computed tomography if suspicion for fracture. Magnetic resonance imaging is modality of choice for detailed evaluation of the soft tissues. Once evaluation is complete, the decision to proceed with operative versus conservative management is made.

We favor surgical reconstruction of the anterior cruciate ligament (ACL) in most patients with more than one ligament injured, but not all patients are appropriate candidates. Some relative contraindications include advanced age, medical contraindications, morbid obesity, and limited functional demand prior to injury. These patients can initially be treated conservatively with immobilization, bracing, and rehabilitation. Surgery can be a viable option in a delayed fashion if patients are experiencing chronic instability.

35.2 Timing of Surgery

The optimal timing of surgery varies considerably depending on nature of the injury, vascular status of the affected extremity, degree of swelling, soft tissue and condition of the skin, degree of instability, and surgeon preference. Some surgeons prefer early operative intervention at approximately 1–2 weeks to allow for repair of injured structures [1]. However, early surgery can be associated with arthrofibrosis. A recent systematic review of the literature suggested that delayed reconstruction of severe multiple-ligament knee injuries resulted in equivalent stability outcomes

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and resulted in lower rates of knee flexion loss after surgery, when compared to acute surgery (within 3 weeks) [2]. Ultimately, the timing of surgical management of the multiligament injured knee is controversial and debatable, and currently there is little evidence to suggest any differences between early versus delayed intervention. Further research is needed to provide definitive recommendations on timing of surgical management, and the decision on timing must be individualized for each patient.

35.3 ACL Graft Selection: Autograft Verses Allograft

In uni-cruciate reconstructions, hamstring or patellar tendon autografts are most frequently used to eliminate the potential risk of graft-host response and disease transmission and have excellent clinical outcomes [3]. However, when considering reconstruction in the multiligament knee, specifically in the three or four ligament injury, we prefer using allograft tissue to reduce donor site morbidity. Allograft tissue provides many benefits over autograft, which include absence of donor site morbidity, less operative time, and multiple graft size options [4]. Fanelli et al. demonstrated that there was no difference in outcomes in patients with autograft versus allograft [1, 5]. However, age remains an important consideration as recent studies have demonstrated that ACL allografts have higher rate of failure (as high as 25 %) when used in patients less than 25 years old [6].

Our preferred graft for the ACL in the multiligament knee is the Achilles, patellar or tibialis anterior tendon allograft. It is important to note that the allograft quality can be heterogeneous. For surgeons in the USA, the supplier should be chosen carefully with adherence to the US Food and Drug Administration/American Association of Tissue Bank guidelines. We have reported no instances of known disease transmission from allograft usage at our institution.

35.4 Surgical Techniques

Prior to surgery, a detailed and thorough ligament examination under anesthesia should be performed, including Lachman, pivot shift, reverse pivot shift, posterior drawer, external rotation drawer, dial test, as well as the degree of varus and valgus opening. If preoperative workup has ruled out vascular injury, we recommend use of a thigh tourniquet during the open part of the procedure.

ACL reconstruction in the multiligament knee is complex for several reasons. Absence of the posterior cruciate ligament (PCL) makes identification of anatomic ACL footprints more difficult. Without the PCL, accurate placement of the notch on the tibia and femur is challenging, and the use of anatomic landmarks to find correct placement and orientation is recommended. Furthermore, when performing transtibial ACL and PCL reconstructions, it is important to leave an adequate bone bridge when drilling the PCL tunnel. Additionally, it is important to leave room for tibial fixation of the ACL on the tibia to avoid overcrowding on the proximal media tibia when doing ACL reconstruction in conjunction with PCL and medial collateral ligament (MCL) reconstructions.

We perform ACL and PCL reconstructions arthroscopically, striving for anatomic reconstruction of both the ACL and the PCL footprints. For the ACL reconstruction, a transtibial or anteromedial portal approach can be utilized depending on whether the transtibial approach can recreate the anatomic femoral footprint. For the PCL, we use a transtibial, single-bundle approach to reproduce the anterolateral bundle (ALB).

We prefer the patient positioned supine on a table with a knee post. Double-bundle ACL reconstruction is contraindicated due to increased risk of tunnel convergence. First, it is helpful to clear anatomic femoral and tibial footprints arthroscopically. Next, a posteromedial accessory portal is established under direct visualization. Then, the shaver and thermal ablation device can be used to debride the tibial stump of the PCL via the posteromedial portal.

Surgeon preference will guide whether one addresses the ACL or the PCL first. We prefer placing the ACL wire in the tibia first, followed by placing the PCL wire in the tibia, with approximately 2 cm between the wires. By placing the ACL pin first, we eliminate the risk that the PCL tunnel will be too proximal on the anterior tibial cortex, which limits the room available for the ACL tunnel. Transtibial PCL tunnel creation is a technically demanding step as optimal pin placement is critical for anatomic restoration of ligaments, and one must carefully avoid the neurovascular structures at risk. When placing the PCL tibial pin, it is important to ensure that an adequate bone bridge is left intact. Once the pins are placed, one can drill the PCL tibial tunnel while fluid pressure is maintained to optimize visualization (and confirm with intraoperative fluoroscopy if needed). This is usually done with visualization through the posteromedial portal, and we recommend using a protector for the reamer. For the femoral PCL tunnel, we attempt to recreate the anterolateral bundle of the PCL using an outside-in minisubvastus approach or an inside-out technique. The femoral PCL tunnel is created at the center of the ALB, approximately 1–2 mm away from the articular margin. The femoral tunnels are drilled last, starting with the ACL and then the PCL. This is also technically challenging as appropriate scope orientation is critical with limited native anatomy to help orient the surgeon. We then ream the ACL tibial tunnel. After both tunnels have been reamed, the ACL and PCL grafts can be passed through their respective tunnels and fixed on the femoral side. A switching stick is used in the posteromedial portal to act as a pulley and facilitate graft passage.

35.5 Fixation

We prefer fixation of the allografts first on the femoral side with interference screws, followed by metallic interference or bioabsorbable screws on the tibial side. We prefer metallic interference screws as they avoid suspensory fixation, are cheaper than bioabsorbable screws, obtain a robust fixation in the cancellous bone, are visible on x-ray, and have minimal bone lysis or inflammatory reactions that can lead to tunnel expansion. After fixation on the femoral side, fixation of the grafts on the tibial side can be done in the following order: the PCL at 90° of flexion, followed by the ACL in full extension, the posterolateral corner, and lastly the medial collateral ligament if indicated.

35.6 Postoperative Rehabilitation

We usually use a post-op hinged knee brace for 6–8 weeks and then transfer patients into a custom brace thereafter for 9–12 months post-op. We allow TTWB for the first 6 weeks then progress to FWB thereafter. We usually lock the brace in full extension for the first week, some of us up to 4 weeks depending on the case, then unlimited ROM thereafter.

References

1. Fanelli GC, Giannotti BF, Edson CJ (1996) Arthroscopically assisted combined anterior and posterior cruciate ligament reconstruction. Arthroscopy 12:5–14
2. Mook WR, Miller MD, Diduch DR, Hertel J, Boachie-Adjei Y, Hart JM (2009) Multiple-ligament knee injuries: a systematic review of the timing of operative intervention and postoperative rehabilitation. J Bone Joint Surg Am 91:2946–2957
3. Hettrich CM, Dunn WR, Reinke EK, Group MOON, Spindler KP (2013) The rate of subsequent surgery and predictors following ACL reconstruction: two- and six-year follow-up from a multicenter cohort. Am J Sports Med 41(7):1534–1540
4. Noyes FR, Barber-Westin SD (1996) Reconstruction of the anterior cruciate ligament with human allograft. Comparison of early and later results. J Bone Joint Surg Am 78:524–537
5. Hudgens JL, Gillette BP, Krych AJ, Stuart MJ, May JH, Levy BA (2013) Allograft versus autograft in posterior cruciate ligament reconstruction: an evidence-based systematic review. J Knee Surg 26(2):109–115
6. Wasserstein D, Sheth U, Cabrera A, Spindler KP (2015) A systematic review of failed anterior cruciate ligament reconstruction with autograft compared with allograft in young patients. Sports Health 7:207–216

36

Scientific Basis and Surgical Technique for Iliotibial Band Tenodesis Combined with ACL Reconstruction

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36.1 Introduction

Although symptomatic instability of the knee following anterior cruciate ligament (ACL) rupture has been known and treated for at least a century [23, 33], the title of this book shows that the best method to treat this complaint remains unresolved, despite a concentrated effort to understand the consequences and treatment of ACL rupture in the last 30 years or so.

It has become clear with hindsight that there have been fundamental shifts of emphasis regarding the treatments used, between lateral extra-articular and central intra-articular procedures. Although there were results of intra-articular ACL reconstruction in response to many injuries occurring during the 1914–1918 war [23], the technical challenges of this surgery and the risk of infection in the joint meant that it was never used widely in that era. Instead, the most common method was to employ a lateral extra-articular tenodesis. The basis for this method was that patients with ACL injury often presented with symptoms of the knee 'giving way'. (This was known as 'slipping knee' prior to the introduction of the term 'pivot shift' by Galway and MacIntosh [13].) The giving-way event was related to abnormal mobility of the lateral compartment, and so it seemed logical to treat the lateral aspect of the knee.

The results of lateral extra-articular procedures, most commonly a lateral extra-articular tenodesis of the iliotibial band (ITB), often left residual instability and measureable anterior

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draw laxity. It may be argued that the biomechanics of the ACL restraint could not be replicated via a lateral extra-articular procedure. It was also the case that surgical methods and rehabilitation protocols were not what they are now. There were historical concerns about ‘stretching out’ of lateral tenodeses, and the resulting residual instability was addressed by prolonged immobilisation in plaster of Paris, usually with the knee held in flexion and external rotation while the tenodesis healed. Unsurprisingly, this led to ongoing problems, and those led to a move back towards intra-articular ACL reconstruction.

The development of arthroscopic procedures, along with dedicated instruments such as drill guides, empowered surgeons to visualise their intra-articular work with unprecedented clarity. The literature moved towards concerns regarding the best graft and intra-articular graft tunnel positions to use on the femur and tibia, with concerns about aspects such as graft isometry [36, 47] and impingement [18].

It may be argued that intra-articular arthroscopic procedures led to a form of ‘tunnel vision’ amongst ACL surgeons, because there have been many studies which attempted to eliminate residual traces of rotational instability post-ACL reconstruction (the ‘pivot glide’) by small changes of intra-articular graft tunnel position, graft tension, or attempts to cover more of the native attachment areas by the use of double-bundle grafts, while ignoring the peripheral structures. There remain some patients whose knees are not restabilised by intra-articular ACL reconstruction alone [22]. It is clinically apparent that not all ACL injuries or knees are the same and that there is a spectrum of severity of soft tissue damage. In fact, given that ACL injury often includes a rotational mechanism, it would be surprising if the peripheral structures were to remain normal. This leads to the conclusion that it may be appropriate, in selected cases, to add a lateral extra-articular procedure to augment the restraint provided by the intra-articular ACL graft.

Clinical studies have evaluated the effect of a combined surgical approach, with mixed results. Some studies suggest that there is a clinical benefit of adding a lateral procedure. Using intraoperative kinematic analysis. Bignozzi et al. [3] found better knee stability with a combined procedure than with an isolated intra-articular procedure – both using hamstring autografts. At the time of surgery, the stabilising effect of the combined procedure was significant on translation of the lateral compartment during Lachman testing and AP translation in 90° of flexion. Using a similar combined technique, Zaffagnini et al. [48] found better subjective outcomes and faster return to sports when compared to a sole intra-articular reconstruction. Vadalà et al. [45] randomised 55 patients to reconstruction with and without an additional MacIntosh tenodesis. At a mean of 44 months after surgery, the group with the tenodesis had significantly less residual rotational laxity – 18 % pivot glide compared to 57 % in the group without a tenodesis. A systematic review has reported significantly less prevalence of residual pivot shifts after combined procedures than isolated ACL reconstructions [41]. Therefore, there is clinical evidence to support the use of a combined procedure, even if the indications are not yet agreed.

This chapter provides a review of the relevant anatomy and biomechanics, leading to a surgical technique for lateral iliotibial band tenodesis.

36.2 Anatomy

There have been differing descriptions of the anatomy of the soft tissue structures at the lateral aspect of the knee, due to the inherent complexity and variability of the anatomy here and perhaps also due to the effects of different dissection approaches and interpretations. It is perhaps best to describe the structures in terms of tissue layers, from superficial to deep.

The iliotibial band (ITB) is a wide fascial band passing along the lateral aspect of the thigh. As it approaches the knee, the ITB spreads out anteriorly, as a lateral retinacular sheet of fascia which sweeps onto the lateral aspect of the vastus lateralis, patella, and patellar tendon. Posterior to this area, the principal fibres of the superficial ITB pass directly to their tibial attachment at Gerdy’s tubercle. The ITB is not completely free to move across the lateral aspect of the knee when it flexes and extends, because it is tethered by further deep attachments. Proximally, there are fibres linking the ITB to the

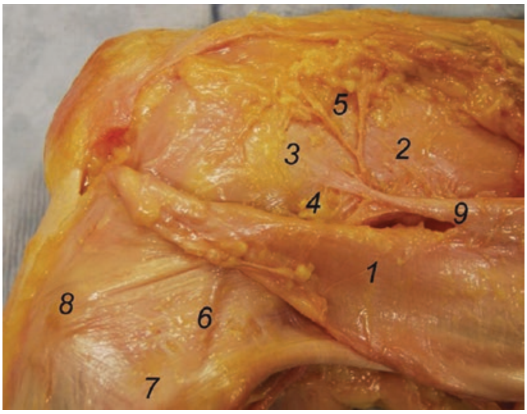

Fig. 36.1 Lateral aspect of a left knee. The superficial layer (*1*) of the iliotibial band (ITB) has been flapped down, revealing the Kaplan fibres. The lateral superior genicular artery (*5*) passes through the lateral intermuscular septum (*9*) between the proximal (*2*) and supracondylar insertion (*3*). The retrograde insertion (*4*; capsulo-osseous layer) forms a sling around the posterolateral femur and inserts distally somewhat posterior to Gerdy's tubercle (*8*). Lateral collateral ligament (*6*); fibular head (*7*) (Reprinted from [26], with permission from Sage Publications)

linea aspera of the femur (lateral intermuscular septum). As the femur reaches the metaphyseal zone, the deep fibres condense into distinct structures – Kaplan's fibres – which act as restraints to movement of the ITB (Fig. 36.1). It is clear that they are arranged in slanting orientation to resist axial movement, in addition to limiting anterior-posterior movement with knee extension-flexion. There are further deep attachments as the ITB reaches the level of the patella: this is where the lateral retinacular fibres which are most commonly released pass in a lateral direction from the lateral edge of the patella to the deep aspect of the ITB [32].

If the ITB is split along its fibres, on the anterior edge of the band which passes to Gerdy's tubercle, the cut edge may be reflected posteriorly, and that manoeuvre reveals the deep structure of the ITB, which has been referred to as the capsule-osseous layer of the ITB [43]. There is effectively a strong link from its attachment at Gerdy's tubercle and posterior to it (which is the area of the Segond avulsion), along the deep aspect of the ITB, to the Kaplan fibre attachments to the lateral side of the femoral metaphysis. This band is obviously tightened by tibial internal rotation. This band is functionally distinct from the superficial layer of the ITB, due to its attachments to the distal-lateral femur, and is not a distinct tissue layer which may be separated from the superficial layer of the ITB.

Removal of the ITB exposes the capsular and other deep structures. There has been much recent interest in the anterolateral ligament (ALL), which has been described by Claes et al. [6] and others [9, 16, 46], with differing interpretations. The present authors have consistently found an ALL which has a femoral attachment that is a mean of 8 mm proximal and 4 mm posterior to the lateral epicondyle [9], although it should be noted that these measurements are variable between knees, with attachments varying from proximal to posterior to the epicondyle [7]. The ALL then passes over (superficial to) the lateral (fibular) collateral ligament (LCL) and courses down to a distal attachment to the tibia, midway between the distal fibular attachment of the LCL and Gerdy's tubercle, approximately 10 mm below the joint line. This is the area from which a bone fragment may be avulsed during ACL rupture – the Segond fracture [40]. In its distal part, the ALL passes over the anterolateral aspect of the lateral meniscus, and the ALL has proximal and distal attachments to the rim of the meniscus, leaving a tunnel through which the inferior lateral branch of the genicular artery passes [6, 9].

There has been widespread agreement regarding the distal attachment of the ALL, but the femoral attachment has been subject to debate. Vincent et al. [46] described the ALL as seen via an arthrotomy during knee replacement when, with the patella reflected laterally, a fibrous capsular band was seen, passing antero-distally from the anterior/distal aspect of the epicondyle. Claes et al. [6] also showed their ALL attaching anterior/distal to the epicondyle and described it as a capsular ligament, with no mention of it passing superficial to the LCL. The attachment described by Dodds et al. [9] has been confirmed recently [25], and there is an accumulation of evidence to support this description, although the exact point may vary from proximal to posterior to the epicondyle [7, 25, 38]. This is an important point, because, as with the ACL, the isometry with knee flexion depends principally on the femoral attachment site, and for the ALL to resist the pivot shift, it needs to be tight near to knee extension [27]. This condition is met by an attachment proximal/posterior to the lateral epicondyle, whereas an anterior/distal attachment leads to graft slackening when the knee is extended [9, 27].

The anatomy of the fibrous structures which reinforce the joint capsule remains poorly defined, and this capsular complex has received many names across the years, perhaps most commonly being called the 'mid-third capsular ligament' [19], and has been associated with the avulsion fracture of Segond [40]. Further studies that include transillumination may build on the work of Dodds et al. [9] to provide a more complete understanding of whether the capsular fibres are a significant structure (see biomechanics, below), but recent findings have suggested that the overlying structures may be more important for resisting the pivot shift.

A concluding observation is that some of the variation in the literature regarding the importance of the ALL appears to have originated from differing interpretations of the anatomy, such that several of the structures and layers of tissue described above may have been conflated into 'the ALL complex', and then it appears that what may be loosely termed 'the ALL' is actually a bulkier and stronger structure than the isolated ALL [7, 26].

36.3 Biomechanics

Several studies have investigated the biomechanical rationale for adding a lateral tenodesis to a modern ACL reconstruction. Samuelson et al. [39] found that an intra-articular ACL reconstruction was unable to restore normal stability to an injured knee when a combined simulated anterolateral plus ACL rupture was present. If an extra-articular tenodesis was added, using a strip of the ITB, the rotational instability was eliminated. The converse of this was a cadaver study of isolated ACL injury, which did not find a biomechanical advantage of adding an extra-articular tenodesis to the intra-articular ACL reconstruction [1]. Engebretsen et al. [10] found a load sharing between the extra- and intra-articular structures, suggesting that the load on the ACL graft would be reduced by using such a combination.

Biomechanically, the principal reason to use a lateral extra-articular procedure is to have the best chance to control abnormal tibial internal rotation laxity, which is an important component of the pivot shift [5]; reviews of the results of ACL reconstruction typically report 15 % of cases having residual 'pivot-glide' laxity [12]. The reason for going to the lateral aspect of the knee is that, when the knee is intact, the axis of tibial internal-external rotation is close to the centre of the knee: Kaneda et al. [24] showed that, although the axis moved across the range of knee flexion, on average it was at the tip of the medial tibial intercondylar spine. This means that neither of the cruciate ligaments has sufficient moment arm to control tibial internal-external rotation effectively, and there have been differing conclusions as to whether isolated ACL injury has a significant effect of tibial rotation. In a real injury, the lateral compartment becomes far more mobile than the medial, and so the axis of rotation shifts medially, sometimes beyond the medial border of the knee [4] (Fig. 36.2). This movement of the axis of rotation means that the lateral aspect of the ACL-injured knee moves anteriorly far more than normal in an anterior draw test, giving rise to the descriptive term 'anterolateral rotatory instability' (ALRI), even though the magnitude of the rotation may not be much more than normal.

A corollary of the large moment arm of the lateral extra-articular structures about the axis of tibial internal-external rotation is that they may act as restraints with relatively low tensions. Recent work on the ALL [25, 50] reported that it had a mean tensile strength of only 50–175 N, and so it may not act as a significant restraint in isolation. Conversely, past work on the use of strips of the ITB as an ACL graft [34] showed that it has much greater strength and stiffness, as expected from its large cross-sectional area.

It was noted above that it is important for the lateral extra-articular tenodesis to be relatively tight (i.e. elongated) when the knee is near to

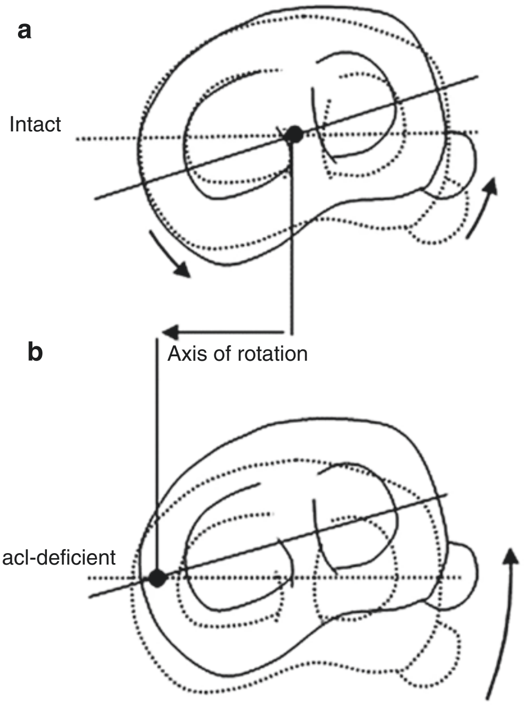

Fig. 36.2 (**a**) The axis of rotation in an ACL intact knee is located at the medial intercondylar spine. (**b**) The axis shifts medially in an ACL-deficient knee, causing a more mobile lateral tibial plateau (Reprinted from [2], with permission from Elsevier)

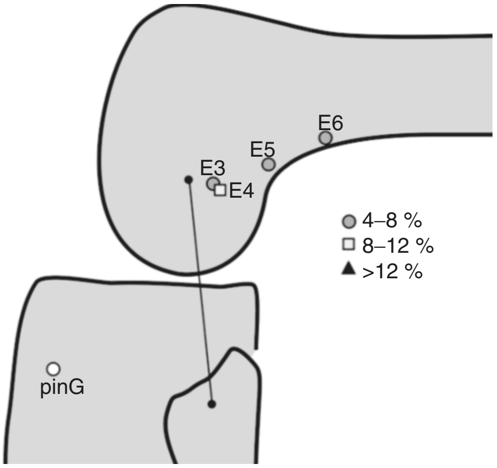

Fig. 36.3 Isometry measurements, expressed as % length change during the range of 0–90° knee flexion, for lateral extra-articular reconstructions. Total strain range (TSR) values were plotted onto the femur. Low values indicate near-isometry and high values show larger length changes. Reconstruction guided deep to the LCL and fixed proximal/posterior to the lateral femoral epicondyle showed favourable graft behaviour (Reprinted from [27], with permission from Sage Publications)

extension, in order to restrain the pivot-shift instability. In general, graft isometry is controlled mainly by the femoral attachment, with posterior points causing tightening in extension, and anterior points causing slackening [49]. The transition between these behaviours lies close to the lateral epicondyle, so that the LCL, for example, slackens slowly with knee flexion [42]. The proximal/posterior attachment of the ALL identified by Dodds et al. [9] was found to cause the ALL to be tight from 0 to 60° knee flexion and then to lead to slackening. Similar findings came from the more complete study by Kittl et al. [27], who also examined several lateral extra-articular tenodeses. In particular, they showed that grafts passed deep to the LCL, which is not an anatomical path, could be attached proximally/posteriorly to the femur and have consistent behaviour with slow tightening of approximately 3 mm as the knee extended, the LCL proximal attachment acting like a pulley to control isometry (Fig. 36.3). That appears to be a good surgical method to adopt, because the graft elongation behaviour was insensitive to the site of bone attachment.

A key biomechanical question is ‘which structures are the primary restraints to tibial internal rotation?’ In order to answer this, it is necessary to perform what is known as a ‘cutting study’, in which the movement being restrained – in this case tibial internal rotation – is repeated exactly, while the possible restraining structures are cut sequentially. This is an ideal application for a robot, which records the path of motion of the native knee and can repeat it and then measure the drop in load caused by cutting each structure. This method has been used to show that the primary restraint to tibial internal rotation was the ITB, with varying contributions from the deep and superficial layers as the knee flexed, but with a combined restraint of approximately 75 % of the total torque imposed [26] (Fig. 36.4). The ACL was a significant restraint only in full knee extension. When all of the structures which have been identified as the ALL and related capsule were examined, their total contribution to resisting

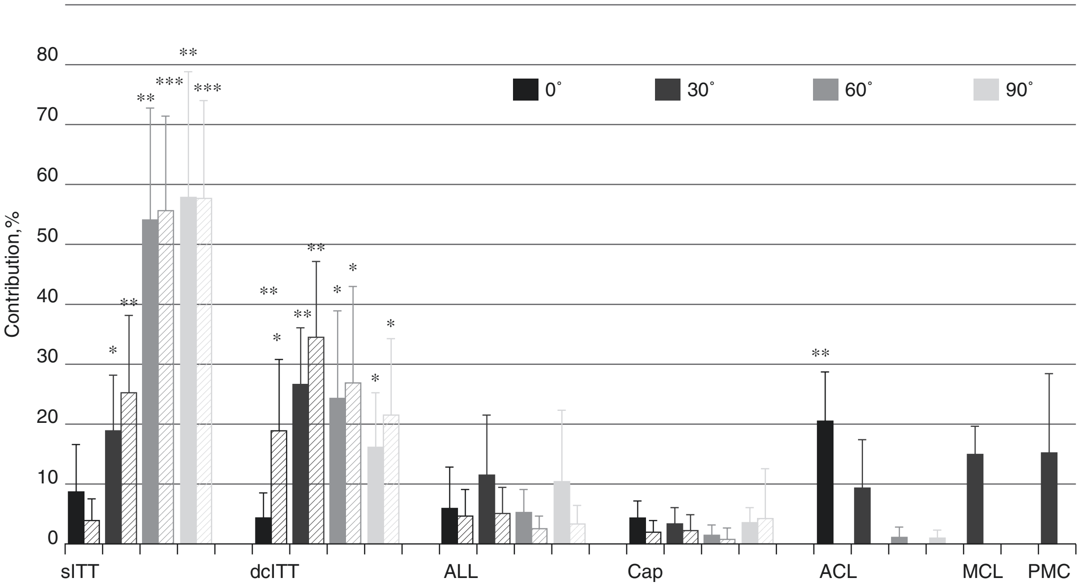

Fig. 36.4 Contributions of the anterolateral structures in controlling a 5 Nm internal rotation torque at 0°, 30°, 60°, and 90° knee flexion. Solid columns are data with ACL intact knees ($n=8$); cross-hatched columns indicate results from the ACL-deficient knee ($n=8$). Together the superficial fibres (sITT) and the deep fibres (dcITT) of the iliotibial band provide the primary restraint to internal rotation at 30–90° flexion. Conversely, the anterolateral ligament (ALL) and the anterolateral capsule (Cap) show a non-significant contribution in restraining internal rotation. Medial collateral ligament (MCL; $n=4$); posteromedial capsule (PMC; $n=4$) (Reprinted from [26], with permissions from Sage Publications)

internal rotation was approximately 10 % and not statistically significant. Other robotic studies [35, 37] came to a different conclusion, but had either removed the ITB prior to starting their measurements or did not distinguish between the ALL and the capsulo-osseous fibres of the ITB inserting at the same tibial attachment site.

It should be noted that the method described above is measuring the load required to create a given tibial displacement and thus allows the restraining load in each structure to be found. The structure carrying most of the load is the *primary restraint*. That method is not the same as in clinical examination, when the examiner usually imposes a standard load and measures the change of displacement, or laxity. In the latter design, the primary restraint may be ruptured, but the knee may remain close to normal laxity under the relatively small forces imposed by hand, and the result will be cutting sequence dependent. Thus, if all structures other than the ALL have been cut, there will be a large increase in laxity when it is finally cut, but that does not mean that it carried much load when acting in concert with the other structures, particularly the overlying ITB, pre-injury.

36.4 Surgical Procedures

Historical descriptions of extra-articular surgical treatment for ACL insufficiency included various techniques that involved the use of the ITB. The idea behind these reconstructions is to reduce the anterior subluxation of the lateral tibial plateau. Therefore, a strip of the ITB was passed deep to the LCL and fixed on the lateral femur. This tethered the ITB posterior to the flexion-extension axis in order to control the anterolateral rotatory instability. This reduction of the anterior subluxation of the lateral tibial plateau has been shown in an experiment, when inserting a K-wire into the femur anterior to the 'Kaplan fibres' (i.e. femoral attachments of the capsulo-osseous ITB) kept the ITB posterior throughout the range of motion. Conversely,

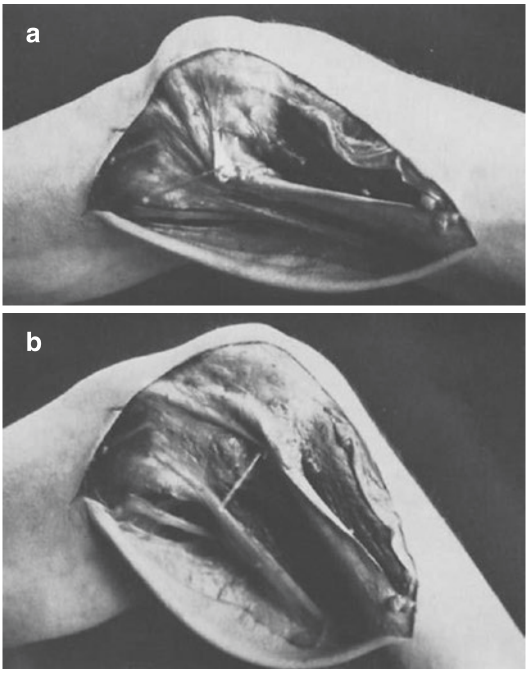

Fig. 36.5 (**a**) When a K-wire was inserted anterior to the Kaplan fibres, the iliotibial band (ITB) reduced the pivot-shift phenomenon, as it provided a posterior vector throughout the range of motion. (**b**) Conversely, when inserting it posterior to the Kaplan fibres, the reduced anterior force vector of the ITB could not reduce the subluxation, even at 80° flexion (Reprinted from [15], with permission from Springer)

when the K-wire was inserted posterior to the Kaplan fibres, the subluxation was still present [15] (Fig. 36.5).

Isolated lateral extra-articular procedures have largely been left behind due to poor patient outcomes and residual laxity in anterior translation, since the intra-articular ACL deficiency was unaddressed. For a while they were combined with intra-articular ACL reconstructions, but in time due to the success of intra-articular ACL reconstruction, the added extra-articular procedure was abandoned by most surgeons as it was thought superfluous and a source of morbidity. There have, however, been more recent attempts to combine intra-articular ACL reconstruction with anterolateral procedures. Although results have been mixed, some studies suggest a positive effect on knee rotational stability and patient-related outcomes [3, 41, 45, 48].

A recent biomechanical comparison of anterolateral procedures combined with ACL reconstruction compared modern modifications of the ITB- based MacIntosh and Lemaire procedures with an anatomic ALL reconstruction using a hamstrings autograft [20]. A combined anterolateral and intra-articular ACL lesion was created in the knees to simulate the combined injured state that is likely to be present in a knee with a significant anterolateral rotatory laxity [31, 44]. A subsequent ACL reconstruction using an AM-portal technique and a patellar tendon graft placed via the centre of the tibial ACL attachment and the AM-bundle position in the femoral attachment was unable to restore the intact knee biomechanics, leaving residual laxity for anterior translation and internal rotation. An ALL reconstruction, based on the anatomic findings of Dodds et al. [9], was added as a conjunct procedure, but only showed a minor additional effect on knee laxity. When instead combining the ACL reconstruction with either a modified MacIntosh or a Lemaire procedure, both utilising a mid-strip of the ITB, residual laxities from ACL reconstruction alone were normalised. In the following section we will therefore elaborate on these two techniques.

The MacIntosh procedure, probably the most well-known lateral tenodesis in the English-speaking world, was credited to MacIntosh and described by Galway et al. [14] in 1972. In a later thorough description of the technique, a 15-cm-long strip of the ITB was left attached at Gerdy's tubercle, while the free proximal end was passed deep to the LCL and placed under a periosteal flap that was created in the proximal part of the lateral epicondyle [21]. The strip was further passed around the bony insertion of the intramuscular septum and twisted several times before it was sutured back onto the soft tissue. The modified MacIntosh procedure used in the above biomechanical study, and in clinical practice by the authors, is based on an approximately 12-cm-long and 10–15-mm-wide central strip of the ITB left attached to Gerdy's tubercle that is carefully dissected and elevated from the underlying tissue. It is important to be aware of the close relations to the femoral insertions of the ITB, the so-called Kaplan fibres, and care should be taken not to injure any remaining parts of these while performing the surgery [30]. The ITB strip is then passed deep to the LCL and attached to the distal area of the femoral shaft at the posterior/lateral aspect. The authors prefer fixation using a staple, so that the remaining part of the graft can be 'doubled back' and sutured back onto itself, reinforcing the construct. Finally the graft-harvesting defect in the ITB should be closed to avoid any herniation of the vastus lateralis muscle.

In the original description of the MacIntosh procedure, the graft was pulled 'as tight as possible' and the knee was held in external rotation at final graft fixation [21]. Thereafter a plaster of Paris cast was applied to the knee, keeping it in 30° of external rotation for 6 weeks before removal. An AOSSM consensus meeting in 1989 (at the end of the era of extra-articular ACL surgery) mentioned a perceived risk of lateral osteoarthritis (OA) and over-constraint of the knee that was held by knee surgeons of that time [11]. Given the above description, where the graft was pulled 'as tight as possible' at final fixation and the knee was immobilised in external rotation, it would not be surprising if OA of the lateral compartment was seen secondary to over-constraint and fixed external rotation. Also at the time, many knees had had prolonged periods of instability and had lost their lateral meniscus. Furthermore, it seems logical that an unsuitable graft positioning (i.e. anterior/distal to the femoral LCL insertion site for the anterolateral ligament reconstruction when a graft is not taken deep to the LCL) or graft over-tensioning may over-constrain the lateral compartment of the knee. Thus, surgeons should be careful to avoid over-constraining the knee when performing these techniques. There is, however, very limited hard evidence to link lateral procedures to an increase in the risk of OA [11, 17].

In light of the fear of over-constraint and OA related to the lateral procedures, there is a surprising paucity of literature investigating such potential adverse effects. The only study that has investigated the effect of varying graft tension [39] used both 0 N and 22 N for tensioning the graft, and the kinematic pattern of the knee was recorded. With 22-N tension, both anterior translation and internal rotation were over-constrained. In light of the lack of evidence, the present authors performed a study evaluating both the kinematic effects and intra-articular pressure changes of varying (1) graft tension and (2) the rotational position of the leg at the time of graft fixation (*unpublished*). When a simulated anterolateral lesion was created, significant increases were found in both anterior tibial translation and internal rotation. A significant drop in lateral tibiofemoral compartment pressure was recorded – representing the loosening of the anterolateral aspect of the knee. A MacIntosh tenodesis performed both with 20-N and 80-N graft tensioning with the knee held in neutral rotation at final graft fixation restored intact knee kinematics and left normal tibiofemoral contact pressures. However, when the knee was left free hanging during graft fixation, when it could move into external rotation, 80 N of graft tensioning led to over-constraint of internal rotation and increased the lateral tibiofemoral contact pressures. It therefore seems that controlling the tibial position at the time of graft fixation is the key to avoiding over-constraining the knee at the time of surgery – more so than the force used for tensioning the graft.

The Lemaire extra-articular technique from 1967 [28] used a 10-mm-wide strip of the ITB that was dissected out and reinforced with a nylon band before it was sutured in place using a drillhole in the posterior part of the lateral epicondyle. This description involved an ITB path superficial to the LCL, while later publications referencing the work of Lemaire describe the graft passing deep to the LCL [8, 29]. The latter technique, also used in the biomechanical study above, is like the MacIntosh procedure in many aspects. A 6–8-cm-long central strip of the ITB left attached at Gerdy's tubercle will usually be sufficient for this procedure and can therefore be utilised as a minimally invasive procedure using a 3–4 cm skin incision to provide a 'mobile window' for surgical exposure (Fig. 36.6). After careful dissection and passing a scissor deep to the LCL without opening the joint cavity nor damaging the popliteus, in our technique a suture anchor is placed in a point just proximal and pos-

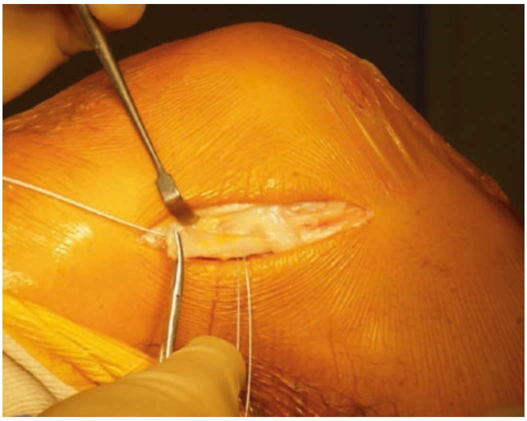

Fig. 36.6 View of the lateral aspect of a right knee at 90° flexion: the femur is to the left and the tibia towards the bottom, right of the picture. A 60–80-mm-long strip of the ITB, left attached on Gerdy's tubercle, is guided deep to the lateral collateral ligament (LCL) and attached proximal and posterior to the femoral LCL insertion site using a suture anchor

Fig. 36.7 Sagittal plane MRI showing that the modified MacIntosh procedure graft is oriented approximately parallel to (i.e. synergistically to) the ACL as it crosses the lateral joint line, proximal to the head of the fibula

terior to the lateral epicondyle so that the graft can be tensioned and fixed to this point once passed deep to the LCL. Alternatively, an interference screw may be used in a tunnel. However, this may risk a tunnel conflict with the intra-articular ACL reconstruction. In both the modified MacIntosh and modified Lemaire procedures, once the graft has been fixed to the bone, the excess graft is turned back and sutured to itself. Graft fixation is undertaken with the knee at 30° flexion and with neutral tibial rotation. The graft will then be oriented approximately parallel to the ACL in the sagittal plane (Fig. 36.7), so it can be expected to act synergistically with it. Since the graft spans the growth plate, the MacIntosh cannot be used in the skeletally immature patient as it will cause growth arrest by a tethering effect. However using intra-operative X-ray, the suture anchor for the modified Lemaire technique can be placed distal to the growth plate.

Little is known about patient selection for these combined procedures. The question arises as to which patients should have additional lateral tenodeses, as many will not need them. There is no evidence-based decision-making process as yet, and therefore our strategy is to add a tenodesis whenever there is perceived higher-than-usual risk of intra-articular graft re-rupture. Skeletally immature ACL reconstruction cases have a much higher intra-articular graft re-rupture rate than skeletally mature cases in our experience, and so extra-articular tenodesis is a useful addition to the intra-articular procedure. As well as the skeletally immature, it may be favourable to use an additional lateral extra-articular soft tissue reconstruction in revision ACL surgery, as it shares the load with the intra-articular graft. Another possible utilisation would be chronic ACL injuries, which display excessive anterolateral rotatory instability due to long-term stretching out of these anterolateral structures. An acute ACL/anterolateral structure rupture, which presents a high-grade pivot shift, and others such as hyperextenders, those with a small pivot shift in the uninjured knee, valgus limb malalignment, and excessive general ligament laxity may benefit from this additional extra-articular procedure. MRI signs for an acute anterolateral injury may include a pronounced lateral femoral condylar notch fracture or haematoma in the tissues deep to the ITB, indicating a severe internal tibial rotation trauma. However, the lack of definitive studies means that there remains a lack of agreement for diagnostic purposes and, hence, a lack of data on the prevalence of these injuries.

Unlike the historic postoperative regimes including lengthy periods in a cast, if a tenodesis is added, we do not change the post-op rehabilitation from that following simple intra-articular ACL reconstruction. Full active extension is sought as soon as possible with full passive extension until this time, flexion increases as tolerated, no immobilisation/bracing, and full weight bearing from the outset (unless there are other reasons for restricted weight bearing).

Conclusions

1. Due to the complex anatomy of the anterolateral structures and their varying description, to date a standardised classification/nomenclature of these structures does not exist. It seems, however, best to describe these in terms of tissue layers from superficial to deep.
2. The ITB is the primary restraint in controlling internal tibial rotation. In particular the deeper iliotibial tract fibres imply a potent role in restraining the subluxation process of the lateral tibial plateau in the pivot-shift phenomenon.
3. The ALL was originally described as a capsular thickening and may have been overestimated in its role of restraining internal rotation.
4. The restraint provided by the anterolateral structures may be restored by a nonanatomical ITB tenodesis, using a strip of the ITB, left attached at Gerdy's tubercle, tunnelled deep to the LCL, and attached proximal/posterior to the lateral femoral epicondyle.

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References

1. Amis A, Scammell B (1993) Biomechanics of intra-articular and extra-articular reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br Vol 75:812–817
2. Amis AA, Bull AM, Lie DT (2005) Biomechanics of rotational instability and anatomic anterior cruciate ligament reconstruction. Oper Tech Orthop 15(1):29–35
3. Bignozzi S, Zaffagnini S, Lopomo N, Martelli S, Iacono F, Marcacci M (2009) Does a lateral plasty control coupled translation during antero-posterior stress in single-bundle ACL reconstruction? An in vivo study. Knee Surg Sports Traumatol Arthrosc 17(1):65–70
4. Bull A, Earnshaw P, Smith A, Katchburian M, Hassan A, Amis A (2002) Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br Vol 84(7):1075–1081
5. Bull AM, Amis AA (1998) The pivot-shift phenomenon: a clinical and biomechanical perspective. Knee 5(3):141–158
6. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J (2013) Anatomy of the anterolateral ligament of the knee. J Anat 223(4):321–328
7. Daggett DO, Ockuly AC, Cullen M, Busch K, Lutz C, Imbert P, Sonnery-Cottet B (2015) Femoral origin of the anterolateral ligament: an anatomic analysis. Arthroscopy. http://dx.doi.org/10.1016/j.arthro.2015.10.006
8. Dejour H, Dejour D, Aït SST (1999) Chronic anterior laxity of the knee treated with free patellar graft and extra-articular lateral plasty: 10-year follow-up of 148 cases. Rev Chir Orthop Reparatrice Appar Mot 85(8):777–789
9. Dodds A, Halewood C, Gupte C, Williams A, Amis AA (2014) The anterolateral ligament: anatomy, length changes and association with the Segond fracture. Bone Joint J 96(3):325–331
10. Engebretsen L, Lew WD, Lewis JL, Hunter RE (1990) The effect of an iliotibial tenodesis on intraarticular graft forces and knee joint motion. Am J Sports Med 18(2):169–176
11. Ferretti A (2014) Extra-articular reconstruction in the anterior cruciate ligament deficient knee: a commentary. Joints 2(1):41
12. Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR (2003) Arthroscopic anterior cruciate ligament reconstruction a metaanalysis comparing patellar tendon and hamstring tendon autografts. Am J Sports Med 31(1):2–11
13. Galway H, MacIntosh D (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
14. Galway R, Beaupre A, MacIntosh D (1972) Pivot shift: a clinical sign of symptomatic anterior cruciate insufficiency. J Bone Joint Surg (Brit) 54(4):763–764
15. Hassler H, Jakob R (1981) Ein beitrag zur ursache der anterolateralen instabilität des kniegelenkes. Arch Orthop Trauma Surg 98(1):45–50
16. Helito CP, Demange MK, Bonadio MB, Tírico LEP, Gobbi RG, Pécora JR, Camanho GL (2013) Anatomy and histology of the knee anterolateral ligament. Orthop J Sports Med 1(7):2325967113513546

17. Hewison CE, Tran MN, Kaniki N, Remtulla A, Bryant D, Getgood AM (2015) Lateral extra-articular tenodesis reduces rotational laxity when combined with anterior cruciate ligament reconstruction: a systematic review of the literature. Arthrosc: J Arthrosc Relat Surg 31(10):2022–2034
18. Howell S, Taylor M (1993) Failure of reconstruction of the anterior cruciate ligament due to impingement by the intercondylar roof. J Bone Joint Surg (Am) 75(7):1044–1055
19. Hughston JC, Andrews J, Cross M, Moschi A (1976) Classification of knee ligament instabilities. Part II. The lateral compartment. J Bone Joint Surg (Am) 58(2):173–179
20. Inderhaug E, Stephen J, Williams A, Amis AA (2016) Biomechanical comparison of anterolateral procedures with ACL reconstruction. Am J Sports Med in press 29 June 2016
21. Ireland J, Trickey E (1980) Macintosh tenodesis for anterolateral instability of the knee. J Bone Joint Surg (Br Vol) 62(3):340–345
22. Jaureguito JW, Paulos LE (1996) Why grafts fail. Clin Orthop Relat Res 325:25–41
23. Jones R (1916) VI. Disabilities of the knee joint. Br Med J 2(2901):169–172
24. Kaneda Y, Moriya H, Takahashi K, Shimada Y, Tamaki T (1997) Experimental study on external tibial rotation of the knee. Am J Sports Med 25(6):796–800
25. Kennedy MI, Claes S, Fuso FAF, Williams BT, Goldsmith MT, Turnbull TL, Wijdicks CA, LaPrade RF (2015) The anterolateral ligament an anatomic, radiographic, and biomechanical analysis. Am J Sports Med 0363546515578253
26. Kittl C, El-Daou H, Athwal KK, Gupte CM, Weiler A, Williams A, Amis AA (2015) The role of the anterolateral structures and the ACL in controlling laxity of the intact and ACL-deficient knee. Am J Sports Med 0363546515614312
27. Kittl C, Halewood C, Stephen JM, Gupte CM, Weiler A, Williams A, Amis AA (2015) Length change patterns in the lateral extra-articular structures of the knee and related reconstructions. Am J Sports Med 43(2):354–362
28. Lemaire M (1967) Ruptures anciennes du ligament croise anterieur du genou. J Chir 93:311–320
29. Lemaire M, Combelles F (1980) Technique actuelle de plastie ligamentaire pour rupture ancienne du ligament croisé antérieur. Rev Chir Orthop 66:523–525
30. Lobenhoffer P, Posel P, Witt S, Piehler J, Wirth C (1987) Distal femoral fixation of the iliotibial tract. Arch Orthop Trauma Surg 106(5):285–290
31. Mansour R, Yoong P, McKean D, Teh JL (2014) The iliotibial band in acute knee trauma: patterns of injury on MR imaging. Skelet Radiol 43(10):1369–1375
32. Merican A, Amis A (2008) Anatomy of the lateral retinaculum of the knee. J Bone Joint Surg Br Vol 90(4):527–534
33. Murray MM (2013) History of ACL treatment and current gold standard of care. In: The ACL handbook. Springer, New York, pp 19–28
34. Noyes FR, Butler DL, Grood ES, Zernicke R, Hefzy M (1984) Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. J Bone Joint Surg (Am Vol) 66(3):344–352
35. Parsons EM, Gee AO, Spiekerman C, Cavanagh PR (2015) The biomechanical function of the anterolateral ligament of the knee. Am J Sports Med 0363546514562751
36. Penner DA, Daniel DM, Wood P, Mishra D (1988) An in vitro study of anterior cruciate ligament graft placement and isometry. Am J Sports Med 16(3):238–243
37. Rasmussen MT, Nitri M, Williams BT, Moulton SG, Cruz RS, Dornan GJ, Goldsmith MT, LaPrade RF (2015) An in vitro robotic assessment of the anterolateral ligament, Part 1 secondary role of the anterolateral ligament in the setting of an anterior cruciate ligament injury. Am J Sports Med 0363546515618387
38. Runer A, Birkmaier S, Pamminger M, Reider S, Herbst E, Kunzel KH, Brenner E, Fink C (2015) The anterolateral ligament of the knee: a dissection study. Knee. http://dx.doi.orh/10.1016/j.knee.2015.09.014
39. Samuelson M, Draganich LF, Zhou X, Krumins P, Reider B (1996) The effects of knee reconstruction on combined anterior cruciate ligament and anterolateral capsular deficiencies. Am J Sports Med 24(4):492–497
40. Segond P (1879) Recherches cliniques et expérimentales sur les épanchements sanguins du genou par entorse. Aux Bureaux du Progrès Médical 1–85
41. Song GY, Hong L, Zhang H, Zhang J, Li Y, Feng H (2015) Clinical outcomes of combined lateral extra-articular tenodesis and intra-articular anterior cruciate ligament reconstruction in addressing high-grade pivot-shift phenomenon. Arthroscopy. http://dx.doi.org/10.1016/j.arthro.2015.08.038
42. Sugita T, Amis AA (2001) Anatomic and biomechanical study of the lateral collateral and popliteofibular ligaments. Am J Sports Med 29(4):466–472
43. Terry GC, Hughston JC, Norwood LA (1986) The anatomy of the iliopatellar band and iliotibial tract. Am J Sports Med 14(1):39–45
44. Terry GC, Norwood LA, Hughston JC, Caldwell KM (1993) How iliotibial tract injuries of the knee combine with acute anterior cruciate ligament tears to influence abnormal anterior tibial displacement. Am J Sports Med 21(1):55–60
45. Vadalà AP, Iorio R, De Carli A, Bonifazi A, Iorio C, Gatti A, Rossi C, Ferretti A (2013) An extra-articular procedure improves the clinical outcome in anterior cruciate ligament reconstruction with hamstrings in female athletes. Int Orthop 37(2):187–192
46. Vincent J-P, Magnussen RA, Gezmez F, Uguen A, Jacobi M, Weppe F, Ma'ad F, Lustig S, Demey G, Servien E (2012) The anterolateral ligament of the human knee: an anatomic and histologic study. Knee Surg Sports Traumatol Arthrosc 20(1):147–152
47. Wagner M, Weiler A (2014) Anterolaterale Stabilisierung. Arthroskopie 27(3):198–201
48. Zaffagnini S, Marcacci M, Presti ML, Giordano G, Iacono F, Neri MP (2006) Prospective and random-

ized evaluation of ACL reconstruction with three techniques: a clinical and radiographic evaluation at 5 years follow-up. Knee Surg Sports Traumatol Arthrosc 14(11):1060–1069

49. Zavras TD, Race A, Bull AMJ, Amis AA (2001) A comparative study of 'isometric' points for anterior cruciate ligament graft attachment. Knee Surg Sports Traumatol Arthrosc 9:28–33
50. Zens M, Feucht MJ, Ruhhammer J, Bernstein A, Mayr HO, Südkamp NP, Woias P, Niemeyer P (2015) Mechanical tensile properties of the anterolateral ligament. J Exp Orthop 2(1):7. doi:10.1186/s40634-015-0023-3

37

Anterolateral Ligament Reconstruction: Anatomy, Rationale, Technique, and Outcome

Steven Claes, Robert LaPrade, Peter Verdonk, and Bertrand Sonnery-Cottet

37.1 Anatomical Properties of the Anterolateral Ligament

The first description of the existence of a knee ligamentous structure between the lateral femur and anterolateral tibia was made by Dr. Paul Segond in 1897 [38] when he noticed 'a pearly, resistant, fibrous band' as being attached to the eponymous fracture on the anterolateral tibial rim. In the following decades, the notion of this structure became largely forgotten, until Jack Hughston published his findings on rotatory knee instability patterns in the late 1970s [20, 21]. He described a 'mid-third lateral capsular ligament' intimately attached to the lateral meniscus and divided the structure into meniscofemoral and meniscotibial portions. According to Hughston, this capsular ligament was 'strong and supported superficially by the iliotibial band' [20]. It was thought to play an important role in the so-called 'anterolateral instability' (ALRI) pattern of the knee [21, 33]. However, this clinical term has become obsolete in the last few decades, most likely due to the advent of arthroscopic knee surgery and its inherent predominance for intra-articular pathology just a few years after its description. Although the term 'mid-third lateral capsular ligament' can be sporadically encountered in later literature [16, 25, 31], no further anatomical characterisation, drawings, or photographs were provided. More recently, Vincent et al. [50] reported on their observations during total knee arthroplasty procedures, when the authors noticed 'a relatively consistent structure in the lateral knee, linking the lateral femoral condyle, the lateral meniscus, and the lateral tibial plateau' [50]. The structure was termed the 'anterolateral ligament', a name which has originally been used by Terry et al. [48] in 1989 and later by Vieira et al. [49] in 2007 while describing the 'capsulo-osseous' layer of the iliotibial band (ITB).

In 2013, Claes et al. [8] reported their results of 41 anatomical dissections in search of this presumed anterolateral ligament (ALL) in the human knee joint. The ligament was present in 97 % of the studied knees, coursing in an oblique course from the lateral femur near the lateral epicondyle in the direction towards the anterolateral tibia, attaching roughly at a point midway between Gerdy's tubercle and the fibular head (Fig. 37.1). In brief, the

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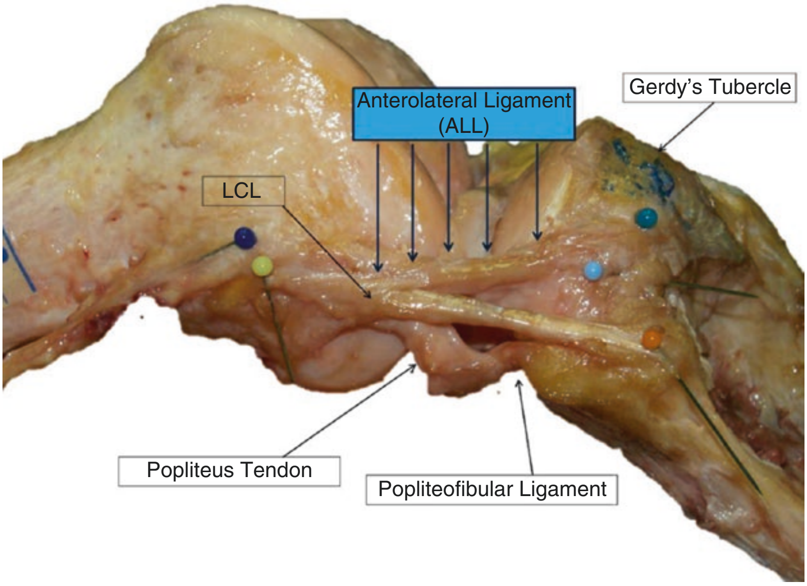

Fig. 37.1 Photograph of a typical right knee after complete dissection of the ALL, popliteus tendon, popliteo-fibular ligament, and lateral collateral ligament (Reused with permission from Claes et al. [8])

ALL was found to be a rather thin ligament (mean thickness 1.3 ± 0.6 mm), with a mean length of 41.5 ± 6.7 mm and a width of 6.7 ± 3.0 mm (in 90° of flexion). Since then, numerous studies have confirmed the existence of the ALL as being a distinct ligamentous structure at the anterolateral side of the human knee [6, 13, 18, 28, 44].

Recently, a study by Kennedy et al. [23] provided a comprehensive quantitative characterisation of the native ALL with regard to anatomy, radiographic landmarks, and biomechanical properties. This study clarifies previous anatomic studies of the ALL that have disagreed regarding the location of its femoral attachment [6, 18], demonstrating that the origin was consistently located 'posterior and proximal to the attachment of the fibular collateral ligament (FCL) and the lateral femoral epicondyle'. Furthermore, the authors defined radiographic attachment locations for eventual surgical ALL reconstruction guidance. At the same time, the biomechanical results of this study found an average maximum load of 175 N for the native ALL thus providing the rationale for the use of standard soft tissue grafts when considering ALL reconstruction as both single-looped semitendinosus and gracilis tendons have been shown to easily exceed this value (1,216 N and 838 N, respectively) [17].

37.2 The Function of the Anterolateral Ligament and the Rationale for Its Reconstruction

37.2.1 The ALL in Rotational Knee Laxity and the Pivot Shift

The pivot shift is a complex, multiplanar phenomenon consisting of a coupled anterior tibial subluxation and excessive internal tibial rotation [4]. To date, the pivot shift is considered the most specific clinical test to assess pathological knee joint rotatory laxity following anterior cruciate ligament (ACL) injury [46], although the deconstruction of the pivot shift in its precise pathological motions has proved amazingly difficult [24]. Furthermore, the pivot shift has been shown to better correlate with functional instability and patient outcomes than any other clinical test [24].

From its first description by Paul Segond in 1879, the ALL has already been associated with rotational control of the knee [7], as he briefly noticed the structure showing 'extreme amounts of tension during forced internal rotation' [38]. Later on, Jack Hughston speculated that 'anterolateral rotatory instability of the knee is caused by a tear of the middle one-third of the lateral capsular ligament' [21], thus minimising the traditional role of the ACL in the pivot-shift phenomenon.

Intuitively, a centrally located cord-like structure like the ACL would indeed be less suited to control the inward rotation of the tibial plane in relation to the femur following the biomechanical principle of the 'wheel and axle'. Given the anatomical course and location of the ALL, one could hypothesise that the ALL functions as a restraint to internal rotation of the tibia relative to the femur and accordingly would play a role in the occurrence of the pivot-shift phenomenon.

In this view, Sonnery-Cottet et al. [41] studied the involvement of the anterolateral knee structures, including the iliotibial band (ITB), the ALL, and the ACL, in internal rotational control of the knee utilising a navigational system for kinematic analysis (Praxim, La Tronche, France). In short, the authors performed a selective ligament sectioning study while analysing internal tibial rotation under a controlled load as well as a standardised pivot-shift test. Their results indeed confirmed that the ALL, as well as the ITB, is involved in rotational control of the knee at varying degrees of knee flexion and during a simulated pivot shift.

Similar findings were previously reported by Monaco et al. [30] who concluded that no significant rotational instability was seen in the ACL-deficient knee until after the lesion to the lateral capsular ligament (i.e. anterolateral ligament) and suggests that 'rotational instability may be due to secondary injuries in conjunction with injuries to the ACL'.

Several authors have further confirmed the restraining effect of the ALL with respect to excessive internal rotation [34, 43].

Rasmussen et al. [35] were the first to expand on the ALL's contribution to the pivot-shift phenomenon utilising a robotic set-up for a simulated clinical examination of the ACL- and ALL-deficient knee. A combined injury to the ACL and ALL resulted in a significant increase in axial plane translation and internal rotation relative to both the intact and ACL-deficient knee. Although this study exhibited some limitations inherent to the biomechanical testing set-up, it concluded that the results regarding the pivot-shift test could explain why a clinically unrecognised injury to the ALL could account for selected cases of residual rotatory instability after an ACL reconstruction.

Most recently, Nitri et al. [32] were the first to perform a biomechanical study on the effect of anatomic ALL reconstruction (ALLR) in the setting of ACL reconstruction. Ten fresh-frozen cadaveric knees were evaluated with a 6° of freedom robotic system performing a simulated pivot-shift test, internal rotation torque, and an anterior tibial load. The authors conclude that 'in the face of a combined ACL and ALL deficiency, concurrent ACLR and ALLR significantly improved the rotatory stability of the knee compared with solely reconstructing the ACL'.

37.2.2 The Rationale for ALL Reconstruction

For a long time, the ACL has been considered as a restraint to both anterior translation and (internal) tibial rotation [10] with the most obvious clinical presentation of ACL-associated rotational instability being the pivot-shift test. According to Tanaka et al. [46] however, 'there is still a paucity of knowledge about the anatomical and morphological features responsible for a high-grade pivot shift'. The pivot shift has been intimately linked with ACL injury since its first description [15], and a positive pivot-shift test result has been shown to carry a specificity of 98 % in detecting ACL lesions [5]. Furthermore, the pivot-shift test result bears a high correlation with final functional outcome after ACL reconstruction [4]. In fact, the presence of a positive pivot-shift test and a rupture of the ACL have almost been considered as synonymous.

With excessive tibial rotation being a quintessential step in producing the pivot shift on one hand, and the notion of the pivot shift being so highly specific for ACL injuries on the other hand, one could indeed deduce that the ACL must control tibial rotation. As explained above, recent information however has demonstrated that the restraining effect of the human ACL on tibial rotation might be relatively negligible [35], a finding actually already published by Wroble et al. [52] in 1993.

The aim of ACL reconstruction lies in eliminating the pivot-shift phenomenon, but the persistence of a positive pivot shift after surgery nowadays remains a significant issue after both single- and double-bundle ACL reconstructions [29, 45]. It is speculated that this persistent rotational laxity, amongst other causes, may explain why only 45–65 % of athletes will return to preinjury activity levels after reconstruction [3]. With the ALL being clearly attributed to the control of internal rotation of the tibia and the prevention of the pivot-shift phenomenon in the ACL-deficient knee [35, 41, 47], concomitant treatment of ALL injuries consequently has become a significant subject of interest in an attempt to improve outcomes after ACL reconstruction.

37.3 ALL Reconstruction: History, Indication, Technique, and Results

37.3.1 The History of ALL Reconstruction: Extra-articular ACL Reconstruction

Confronted with subjects demonstrating post-traumatic anterolateral knee laxity in an era before the advent of knee MRI or arthroscopy, many authors in the 1970s published surgical techniques as a proposed treatment for anterolateral tibial subluxation. These so-called ‘extra-articular’ techniques in ACL reconstruction were, for example, popularised by MacIntosh [9, 22], Losee [26], Ellison [14], and Andrews [2] but have largely been abandoned because of the inconsistency in the reported results. Strikingly, although some of these techniques seemed to adequately address the rotational issue [1], no clearer description or characterisation than ‘anterolateral capsular structures’ was at hand to designate the ligamentous structure they were assumed to reconstruct [12]. In this view, the increasing knowledge surrounding the ALL therefore has the potential to deliver the rationale behind some of these ‘empirically’ extra-articular reconstructions from the past.

37.3.2 Technique and Indications

With increasing knowledge on the ALL, confirming its role as a controller for internal tibial rotation and the pivot-shift phenomenon, a combined treatment regimen for both ACL and ALL has become a significant subject of interest when considering the issue of persistent rotational laxity after ACL reconstruction [27, 30, 35].

In an attempt to integrate these new insights in clinical practice, the authors suggest to consider concomitant ACL and ALL reconstruction in the following:

1. IKDC grade III pivot shift
2. IKDC grade II pivot shift in pivoting athletes
3. Revision ACL surgery, certainly without a history of frank re-trauma or manifest technical errors

As described above, the so-called extra-articular ACL reconstruction techniques, which typically consist of fixing an ITB strip left attached to Gerdy’s tubercle to the lateral femoral metaphysis, might possibly be regarded as ‘nonanatomic ALL reconstructions’. Although an (modified) ITB tenodesis type of ALL reconstruction might indeed restrain excessive internal tibial rotation and the pivot shift, emerging knowledge on precise ALL anatomy and function has driven the development of more anatomic ALL reconstruction techniques as a concomitant procedure to ACL reconstruction surgery [36, 39, 42].

Typically, ALL reconstruction initially begins with an examination under anaesthesia to confirm the presence of rotational instability as demonstrated by a high-grade pivot shift. Basically, the procedure itself consists of fixing an auto- or allograft gracilis tendon on the anatomical attachment sites of the native ALL in both femur and tibia. Both single- and double (‘V’)-strand techniques have been proposed in order to maximally mimic the broader ALL's native footprint on the tibia [39, 40].

The main landmark for the femoral socket is the lateral epicondyle, and a mini-incision over this area in proximal direction is performed. The tibial incision is planned at a point right between Gerdy's tubercle and the fibular head, just distal to the tibial joint line. Through the femoral incision, the IT band is split in line with its fibres, and the lateral collateral ligament (LCL) is identified and protected. For both single- and double-strand ALL reconstructions, a 2.4 mm guidewire is advanced at a point at 8 mm proximal and posterior to the lateral epicondyle right on the femoral origin of the ALL [11, 23]. It is important to avoid convergence with the ACL femoral socket, so it is suggested to drill the femoral ALL socket before ACL graft insertion while aiming somewhat anteriorly and distally. A longitudinal mini-incision and soft tissue dissection are then made at the site of the tibial fixation socket. The 2.4 mm guidewire is then placed on the anatomical insertion of the ALL at about 9 mm distally to the tibial joint line. A suture can be passed deep to the IT band and passed around the pins to check for isometry of the ALL: typically, the ALL will be relatively isometric in extension and slackens from 60° flexion [13]. If satisfactory, then a single femoral and one or two tibial bone sockets are drilled with a 4.5 mm drill to a depth of 20 mm [39].

After having finished the ACL reconstruction procedure, the ALL graft is finally fixed into the femoral and tibial bone sockets using an appropriate tap and 4.75-mm-diameter bioabsorbable fully threaded knotless anchors (SwiveLock BioComposite, Arthrex Inc., Naples, USA). The whipstitched end is secured into the femoral socket, and then the graft is tensioned from the tibial end, after having passed the graft deep to the iliotibial band and through the distal skin incision. Finally, one or more anchors are then used to secure the graft on the tibia while tensioning the graft in full extension (Fig. 37.2). Different techniques for graft fixing might be used with good success as long as the surgeon adheres to the same principles mentioned above.

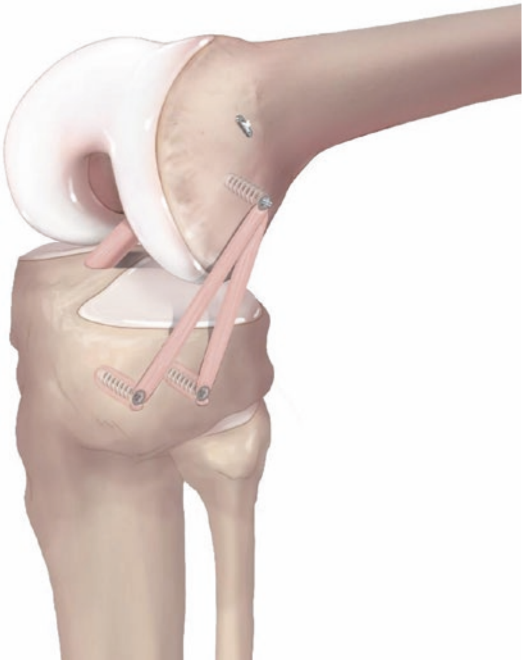

Fig. 37.2 Schematic diagram depicting a double- or 'V'-strand technique for anatomic ALL reconstruction. The gracilis tendon is fixed in a single socket on the femoral origin of the ALL and in two tibial sockets replicating its broader tibial attachment (© 2016, Arthrex GmbH, image used with permission)

37.3.3 Clinical Outcomes of Anatomic ALL Reconstruction

Recently, the clinical results of the first series of combined ACL and ALL reconstruction were published [42]. In a consecutive series of 396 ACL reconstructions performed between January 2011 and January 2012, 92 combined ACL reconstructions with minimally invasive ALL reconstructions were carried out.

Indications for a combined procedure were an associated Segond fracture, a chronic ACL lesion, a grade 3 pivot shift, a high level of sporting activity, participation in pivoting sports, and radiographic sign of a lateral femoral notch. The patients were assessed pre- and postoperatively with objective and subjective International Knee Documentation Committee (IKDC) score, Lysholm score, and Tegner activity scale.

Objective testing for knee laxity was measured with an instrumented knee laxity testing device (Rolimeter arthrometer). Amongst other complications, graft failure and contralateral ACL rupture were recorded.

The mean follow-up was 32.4±3.9 months, with 83 patients available for final evaluation. At the last follow-up, no patient had restricted range of motion. Significant improvement in the Lysholm, subjective IKDC, and objective IKDC scores was noted (all $p < 0.0001$). The mean differential anterior laxity was 8±1.9 mm before surgery and significantly decreased to 0.7±0.8 mm at the last follow-up ($P < 0.0001$). Preoperatively, 41 patients had a grade 1 pivot shift, 23 had grade 2, and 19 had grade 3 according to the IKDC criteria. Postoperatively, 76 patients had a negative pivot shift (grade 0), and 7 patients recorded grade 1 laxity ($P < 0.0001$). Furthermore, after more than 2 years of follow-up, this series shows a contralateral ACL rate rupture (6.6 %) similar to that described in the recent literature [19, 37, 51]. Interestingly however, over the same time period, the ACL graft rupture rate for the combined ACL and ALL reconstruction group was only 1.1 %, which is definitively lower than typically reported.

This pilot study thus demonstrated that a combined ACL and ALL reconstruction can be an effective procedure without specific complications related to the additional ALL reconstruction (e.g. lateral knee pain or stiffness) at a minimum follow-up of 2 years. Although encouraging, more studies are needed to determine whether these combined reconstructions improve the results of ACL treatment over the longer term.

Conclusion

The anterolateral ligament is a distinct anatomical structure in the human knee. It has been reported to act as a important restraint for internal tibial rotation and thus affects the pivot-shift phenomenon in the ACL-deficient knee. With persistent rotational laxity after ACL reconstruction being an incompletely solved issue in contemporary knee surgery, concomitant anatomic ALL reconstruction might have the potential to improve outcomes in rotationally unstable ACL and ALL-deficient knees. Although highly encouraging, more studies are needed to determine whether these combined reconstructions improve the results of ACL treatment over the longer term.

References

1. Amis AA, Scammell BE (1993) Biomechanics of intra-articular and extra-articular reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br Vol 75:812–817
2. Andrews JR, Sanders R (1983) A "mini-reconstruction" technique in treating anterolateral rotatory instability (ALRI). Clin Orthop Relat Res 172:93–96
3. Ardern CL, Taylor NF, Feller JA, Webster KE (2014) Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med 48:1543–1552. doi:10.1136/bjsports-2013-093398
4. Ayeni OR, Chahal M, Tran MN, Sprague S (2012) Pivot shift as an outcome measure for ACL reconstruction: a systematic review. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 20:767–777. doi:10.1007/s00167-011-1860-y
5. Benjaminse A, Gokeler A, van der Schans CP (2006) Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis. J Orthop Sports Phys Ther 36:267–288
6. Caterine S, Litchfield R, Johnson M, Chronik B, Getgood A (2015) A cadaveric study of the anterolateral ligament: re-introducing the lateral capsular ligament. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 23:3186–3195. doi:10.1007/s00167-014-3117-z
7. Claes S, Luyckx T, Vereecke E, Bellemans J (2014) The Segond fracture: a bony injury of the anterolateral ligament of the knee. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 30:1475–1482. doi:10.1016/j.arthro.2014.05.039
8. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J (2013) Anatomy of the anterolateral ligament of the knee. J Anat 223:321–328. doi:10.1111/joa.12087
9. Claes T, Declercq G, Martens M, Lefevre J (1986) Extra-articular ligamentoplasty for chronic ACL insufficiency. Acta Orthop Belg 52:515–525
10. Colombet P, Jenny JY, Menetrey J, Plaweski S, Zaffagnini S (2012) Current concept in rotational laxity control and evaluation in ACL reconstruction. Orthop Traumatol Surg Res: OTSR 98:S201–S210. doi:10.1016/j.otsr.2012.10.005, S1877-0568(12)00232-0 [pii]
11. Daggett M, Ockuly AC, Cullen M, Busch K, Lutz C, Imbert P, Sonnery-Cottet B (2015) Femoral origin of the anterolateral ligament: an anatomic analysis. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc

Assoc N Am Int Arthrosc Assoc. doi:10.1016/j.arthro.2015.10.006

12. Dodds AL, Gupte CM, Neyret P, Williams AM, Amis AA (2011) Extra-articular techniques in anterior cruciate ligament reconstruction: a literature review. JBoneJointSurgBrVol93:1440–1448.doi:10.1302/0301-620x.93b11.27632
13. Dodds AL, Halewood C, Gupte CM, Williams A, Amis AA (2014) The anterolateral ligament: anatomy, length changes and association with the Segond fracture. Bone Joint J 96-b:325–331. doi:10.1302/0301-620x.96b3.33033
14. Ellison AE (1979) Distal iliotibial-band transfer for anterolateral rotatory instability of the knee. J Bone Joint Surg Am 61:330–337
15. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
16. Haims AH, Medvecky MJ, Pavlovich R Jr, Katz LD (2003) MR imaging of the anatomy of and injuries to the lateral and posterolateral aspects of the knee. AJR Am J Roentgenol 180:647–653
17. Hamner DL, Brown CH Jr, Steiner ME, Hecker AT, Hayes WC (1999) Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: biomechanical evaluation of the use of multiple strands and tensioning techniques. J Bone Joint Surg Am 81:549–557
18. Helito CP, Demange MK, Bonadio MB, Tirico LE, Gobbi RG, Pecora JR, Camanho GL (2013) Anatomy and histology of the knee anterolateral ligament. Orthop J Sports Med 1:2325967113513546. doi:10.1177/2325967113513546
19. Hettrich CM, Dunn WR, Reinke EK, Group M, Spindler KP (2013) The rate of subsequent surgery and predictors after anterior cruciate ligament reconstruction: two- and 6-year follow-up results from a multicenter cohort. Am J Sports Med 41:1534–1540. doi:10.1177/0363546513490277
20. Hughston JC, Andrews JR, Cross MJ, Moschi A (1976) Classification of knee ligament instabilities. Part I. The medial compartment and cruciate ligaments. J Bone Joint Surg Am 58:159–172
21. Hughston JC, Andrews JR, Cross MJ, Moschi A (1976) Classification of knee ligament instabilities. Part II. The lateral compartment. J Bone Joint Surg Am 58:173–179
22. Ireland J, Trickey EL (1980) Macintosh tenodesis for anterolateral instability of the knee. J Bone Joint Surg Br Vol 62:340–345
23. Kennedy MI, Claes S, Fuso FA, Williams BT, Goldsmith MT, Turnbull TL, Wijdicks CA, LaPrade RF (2015) The anterolateral ligament: an anatomic, radiographic, and biomechanical analysis. Am J Sports Med. doi:10.1177/0363546515578253
24. Lane CG, Warren R, Pearle AD (2008) The pivot shift. J Am Acad Orthop Surg 16:679–688, doi:16/12/679 [pii]
25. LaPrade RF (1997) Arthroscopic evaluation of the lateral compartment of knees with grade 3 posterolateral knee complex injuries. Am J Sports Med 25:596–602
26. Losee RE, Johnson TR, Southwick WO (1978) Anterior subluxation of the lateral tibial plateau. A diagnostic test and operative repair. J Bone Joint Surg Am 60:1015–1030
27. Lutz C, Sonnery-Cottet B, Niglis L, Freychet B, Clavert P, Imbert P (2015) Behavior of the anterolateral structures of the knee during internal rotation. Orthop Traumatol Surg Res: OTSR 101:523–528. doi:10.1016/j.otsr.2015.04.007
28. Macchi V, Porzionato A, Morra A, Stecco C, Tortorella C, Menegolo M, Grignon B, De Caro R (2015) The anterolateral ligament of the knee: a radiologic and histotopographic study. Surg Radiol Anat: SRA. doi:10.1007/s00276-015-1566-9
29. Meredick RB, Vance KJ, Appleby D, Lubowitz JH (2008) Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis. Am J Sports Med 36:1414–1421. doi:10.1177/0363546508317964
30. Monaco E, Ferretti A, Labianca L, Maestri B, Speranza A, Kelly MJ, D'Arrigo C (2012) Navigated knee kinematics after cutting of the ACL and its secondary restraint. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 20:870–877. doi:10.1007/s00167-011-1640-8
31. Moorman CT 3rd, LaPrade RF (2005) Anatomy and biomechanics of the posterolateral corner of the knee. J Knee Surg 18:137–145
32. Nitri M, Rasmussen MT, Williams BT, Moulton SG, Cruz RS, Dornan GJ, Goldsmith MT, LaPrade RF (2016) An in vitro robotic assessment of the anterolateral ligament, Part 2: anterolateral ligament reconstruction combined with anterior cruciate ligament reconstruction. Am J Sports Med 44:593–601. doi:10.1177/0363546515620183
33. Norwood LA Jr, Andrews JR, Meisterling RC, Glancy GL (1979) Acute anterolateral rotatory instability of the knee. J Bone Joint Surg Am 61:704–709
34. Parsons EM, Gee AO, Spiekerman C, Cavanagh PR (2015) The biomechanical function of the anterolateral ligament of the knee. Am J Sports Med 43:669–674. doi:10.1177/0363546514562751
35. Rasmussen MT, Nitri M, Williams BT, Moulton SG, Cruz RS, Dornan GJ, Goldsmith MT, LaPrade RF (2015) An in vitro robotic assessment of the anterolateral ligament, Part 1: secondary role of the anterolateral ligament in the setting of an anterior cruciate ligament injury. Am J Sports Med. doi:10.1177/0363546515618387
36. Roessler PP, Schuttler KF, Heyse TJ, Wirtz DC, Efe T (2015) The anterolateral ligament (ALL) and its role in rotational extra-articular stability of the knee joint: a review of anatomy and surgical concepts. Arch Orthop Trauma Surg. doi:10.1007/s00402-015-2395-3
37. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K (2005) Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 21:948–957. doi:10.1016/j.arthro.2005.04.110

38. Segond P (1879) Recherches cliniques et expérimentales sur les épanchements sanguins du genou par entorse. Progrès Médical (Paris). Accessible from http://www.patrimoineedilivre.com/. pp 1–85
39. Smith JO, Yasen SK, Lord B, Wilson AJ (2015) Combined anterolateral ligament and anatomic anterior cruciate ligament reconstruction of the knee. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 23:3151–3156. doi:10.1007/s00167-015-3783-5
40. Sonnery-Cottet B, Barbosa N, Tuteja S, Daggett D, Kajetanek C, Thaunat M (2016) Minimally invasive anterolateral ligament reconstruction in the setting of ACL injury. Arthrosc Tech 29;5(1):e211–5. doi:10.1016/j.eats.2015.11.005
41. Sonnery-Cottet B, Lutz C, Daggett M, Dalmay F, Freychet B, Niglis L, Imbert P (2016) The involvement of the anterolateral ligament in rotational control of the knee. Am J Sports Med. doi:10.1177/0363546515625282
42. Sonnery-Cottet B, Thaunat M, Freychet B, Pupim BH, Murphy CG, Claes S (2015) Outcome of a combined anterior cruciate ligament and anterolateral ligament reconstruction technique with a minimum 2-year follow-up. Am J Sports Med. doi:10.1177/0363546515571571
43. Spencer L, Burkhart TA, Tran MN, Rezansoff AJ, Deo S, Caterine S, Getgood AM (2015) Biomechanical analysis of simulated clinical testing and reconstruction of the anterolateral ligament of the knee. Am J Sports Med 43:2189–2197. doi:10.1177/0363546515589166
44. Stijak L, Bumbasirevic M, Radonjic V, Kadija M, Puskas L, Milovanovic D, Filipovic B (2014) Anatomic description of the anterolateral ligament of the knee. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA. doi:10.1007/s00167-014-3422-6
45. Suomalainen P, Jarvela T, Paakkala A, Kannus P, Jarvinen M (2012) Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 5-year results. Am J Sports Med 40:1511–1518. doi:10.1177/0363546512448177
46. Tanaka M, Vyas D, Moloney G, Bedi A, Pearle AD, Musahl V (2012) What does it take to have a high-grade pivot shift? Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 20:737–742. doi:10.1007/s00167-011-1866-5
47. Tavlo M, Eljaja S, Jensen JT, Siersma VD, Krogsgaard MR (2015) The role of the anterolateral ligament in ACL insufficient and reconstructed knees on rotatory stability: a biomechanical study on human cadavers. Scand J Med Sci Sports. doi:10.1111/sms.12524
48. Terry GC, Hughston JC, Norwood LA (1986) The anatomy of the iliopatellar band and iliotibial tract. Am J Sports Med 14:39–45
49. Vieira EL, Vieira EA, da Silva RT, Berlfein PA, Abdalla RJ, Cohen M (2007) An anatomic study of the iliotibial tract. Arthrosc: J Arthrosc Relat Surg: Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 23:269–274. doi:10.1016/j.arthro.2006.11.019, doi:S0749-8063(06)01443-5 [pii]
50. Vincent JP, Magnussen RA, Gezmez F, Uguen A, Jacobi M, Weppe F, Al-Saati MF, Lustig S, Demey G, Servien E, Neyret P (2012) The anterolateral ligament of the human knee: an anatomic and histologic study. Knee Surg Sports Traumatol Arthrosc: Off J ESSKA 20:147–152. doi:10.1007/s00167-011-1580-3
51. Wright RW, Magnussen RA, Dunn WR, Spindler KP (2011) Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. J Bone Joint Surg Am 93:1159–1165. doi:10.2106/JBJS.J.00898
52. Wroble RR, Grood ES, Cummings JS, Henderson JM, Noyes FR (1993) The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee. Am J Sports Med 21:257–262; discussion 263

38

Instrumented Static Laxity Evaluation

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38.1 Introduction

The majority of anterior cruciate ligament (ACL) tears can be diagnosed with a detailed patient history, including the injury mechanism, in association with a thorough clinical examination with side-to-side comparisons. For the physical examination, experience on the part of the examiner is very important. The two most frequently encountered clinical situations are either an acute ACL injury or a chronic anterior laxity. Static laxity measurements are of great clinical interest for those cases in which the clinical examination is uncertain and in order to provide a longitudinal follow-up of patients with or without ACL reconstruction. Over the last 40 years, several methods have been developed to evaluate static knee laxity, which will be described thereafter. Static laxity is evaluated in a single direction after unidirectional force application. Dynamic laxity measurement techniques, which consider knee kinematics after the application of a multidirectional force to the knee joint, will be described in another chapter.

Instrumented laxity measurements provide an objective evaluation of knee laxity, which should – in theory – be superior to the results obtained by physical examination [68]. In reality, both are complementary, and the final diagnosis is a result of multiple sources of information, including clinical examination, laximetry and imaging [28]. As for the two other investigation methods, laximetry may be prone to measurement errors. Therefore, several conditions need to apply for reliable information: the patient needs to be relaxed, and the knee should not acutely be injured, swollen and painful [25].

38.1.1 Sagittal Laxity Measurements

Several non-invasive methods have been described to evaluate anterior tibial translation or sagittal laxity. In this chapter we will describe the most used techniques. As a general principle, the knee should be examined in a supine position and in neutral rotation [26].

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38.1.1.1 KT-1000® and KT-2000® [22] (Fig. 38.1)

The KT-1000® was developed in the 1980s by Daniel et al. [22]. To date, this is the most common device to measure anterior knee laxity. Subjects are tested supine with both knees resting on a support at 30° of flexion. The device is secured to proximal and distal tibia with two Velcro® straps. The KT-1000® measures the anteroposterior displacement between two sensors: one is held by the examiner in contact with the patella, and the other is placed anterior on the tibial tuberosity. The examiner manually applies a force of 67, 89 and 134 N or to the maximal manual force on the shank. Although this device is widely used, its precision and reproducibility have been questioned. Several authors reported an intraclass correlation coefficient (ICC) above 0.8 [35, 65]. The reliability of the device however diminishes if the examiner is not experienced (ICC = 0.65) [14]. In ACL-injured patients, the inter-examiner ICC even decreases to 0.55 [80]. As the force is applied manually, the examiner [11] and its dominant hand [80] seem to critically influence laxity measurements. As such, in certain conditions, it seems that the reliability of the KT-1000® is lower than for the Lachman test [104]. However, with a maximal manual force, the sensitivity and specificity of the device are excellent (93 %) for the diagnosis of ACL injuries [101].

38.1.1.2 Rolimeter® (Aircast Europa, Neubeuern, Allemagne) [10] (Fig. 38.2)

The Rolimeter® is light, easily transportable, cheap and sterilisable. Force application is not calibrated and is done manually. This device is similar to the KT-1000®. The Rolimeter® is considered, along with the KT-1000®, to be the device that provides the best results for anterior laxity [72]. Furthermore, it is as reliable as the KT-1000® [10, 79] even when used by novice examiners [63]. Its sensitivity and specificity in the diagnosis of ACL injuries are similar to the KT-1000® [30] but have been reported to be lower in comparison to the Telos® device [70].

38.1.1.3 GNRB® (Genourob, Laval, France) [73] (Fig. 38.3)

The GNRB® is the first device that proposes a mechanised application of the anterior force under standardised and controlled conditions. The patient lies on a standard examination table in the supine position with the arms placed along the body. The lower limb lies on a composite

Fig. 38.1 Measurement of anterior knee laxity with the KT-1000®

thermoformed support, adaptable to leg length, with the knee in neutral rotation. The knee is placed on the device so that the inferior pole of the patella corresponds to the lower border of the patellar support. The joint line is palpated and is placed between the support and the jack. An electronic jack applies an anterior force of 67, 89, 134, 150 or 250 N to the postero-superior part of the calf. Two skin electrodes record the hamstring muscles activity during the test to avoid any muscular contraction and exclude false negative results [25]. A motion sensor (precision: 0.1 mm) records the relative displacement of the anterior tibial tubercle with respect to the femur. Data obtained from the displacement sensor are collected on a computer. These data include measurement conditions (pressure applied to the patellar, forces) and results (differential laxity in mm, differential slope in μm/N) to reproduce the force-displacement curve (Fig. 38.4).

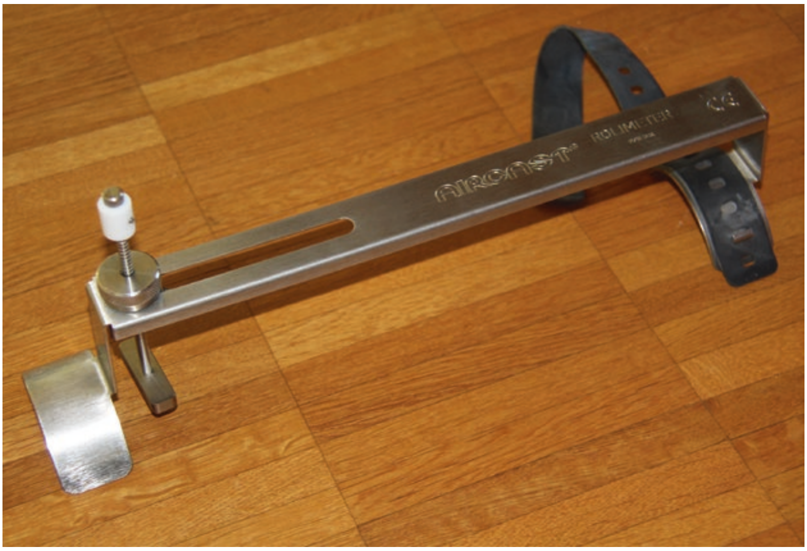

Fig. 38.2 The Rolimeter®: a simple device to measure anterior knee laxity

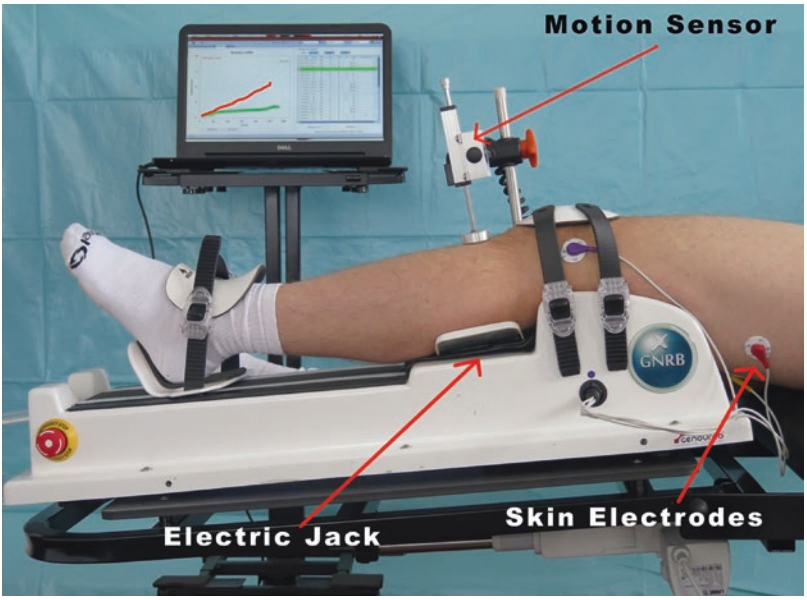

Fig. 38.3 The GNRB®: an electric jack applies an anteriorly directed force while two skin electrodes record the activity of the hamstrings. Anterior displacement is measurement at the tibial tubercle

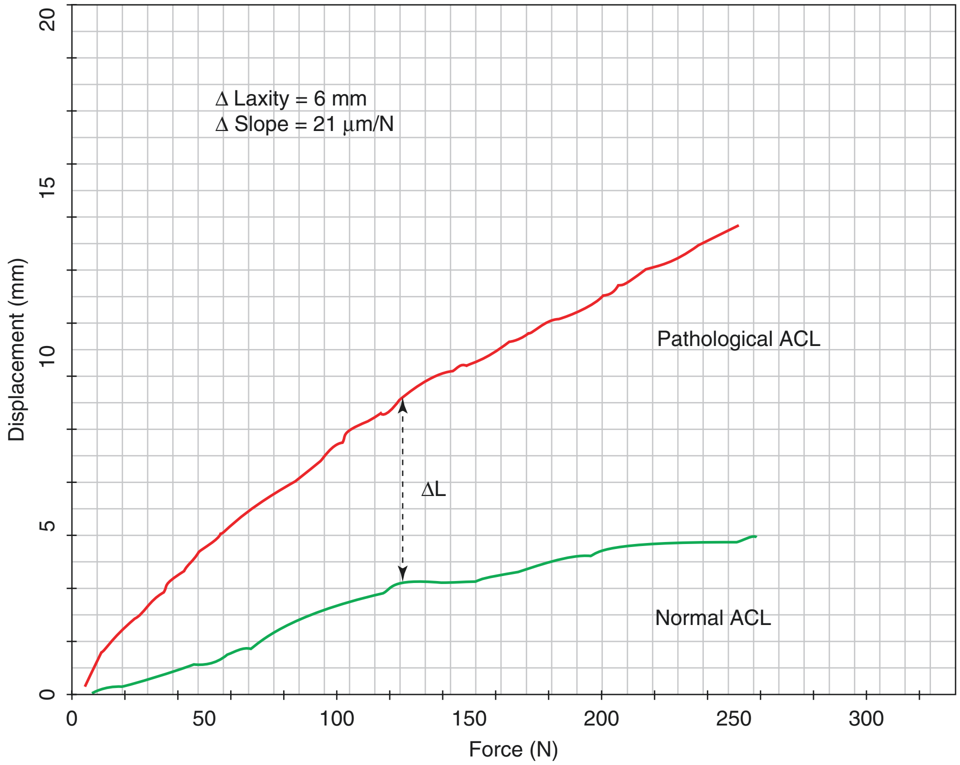

Fig. 38.4 Typical force-displacement curve obtained with the GNRB® in the healthy (*green*) and injured (*red*) knee of an ACL-injured patients with a complete tear

The GNRB® has been reported to have a greater reliability than the KT-1000® regardless of the examiner's experience [20]. However, despite a high intra-examiner ICC, Vauhnik et al. reported a weak inter-examiner ICC inferior to 0.4 which may have been caused by variations in patient installation [102, 103]. To measure anterior knee laxity, an anterior force of 134 N has usually been advised as this represents the standard force with the KT-1000® and because it is well tolerated in acute injuries. For this amount of force and for a side-to-side difference of 3 mm between knees, the GNRB® reaches a sensitivity of 70 % and a specificity of 99 % to detect complete ACL tears [73]. Sensitivity increases to 92.2 % to detect complete ACL tears with a force of 200 N. A similar specificity of 98.1 % can be observed at this force [45]. The GNRB® may also be useful to detect partial ACL tears (Fig. 38.5). At 134 N and for a side-to-side difference of 1.5 mm, a sensitivity of 87 % and a specificity of 87 % could be observed for ruptures of the anteromedial bundle of the ACL [73]. For similar tears, a sensitivity of 72 % was observed by Di Ioro et al. [24]. At 250 N, a side-to-side difference of 2.5 mm provided a sensitivity of 81 % and a specificity of 87 % [49]. As such, the diagnostic power of the GNRB® seems to be similar, or even better, compared to radiographic laxity evaluation methods [41, 49].

38.1.1.4 Radiostereometric Analysis (RSA)

RSA was developed 40 years ago in Sweden by Göran Selvik. This technique is both the most precise and the most invasive method as it requires the surgical implantation of intraosseous tantalum beads of a diameter of 0.8–1.6 mm [93]. They are implanted into the patient's knee at the distal part of the femur and proximal part of the tibia. Two radiographs are performed simultaneously, and the anatomical position of the markers

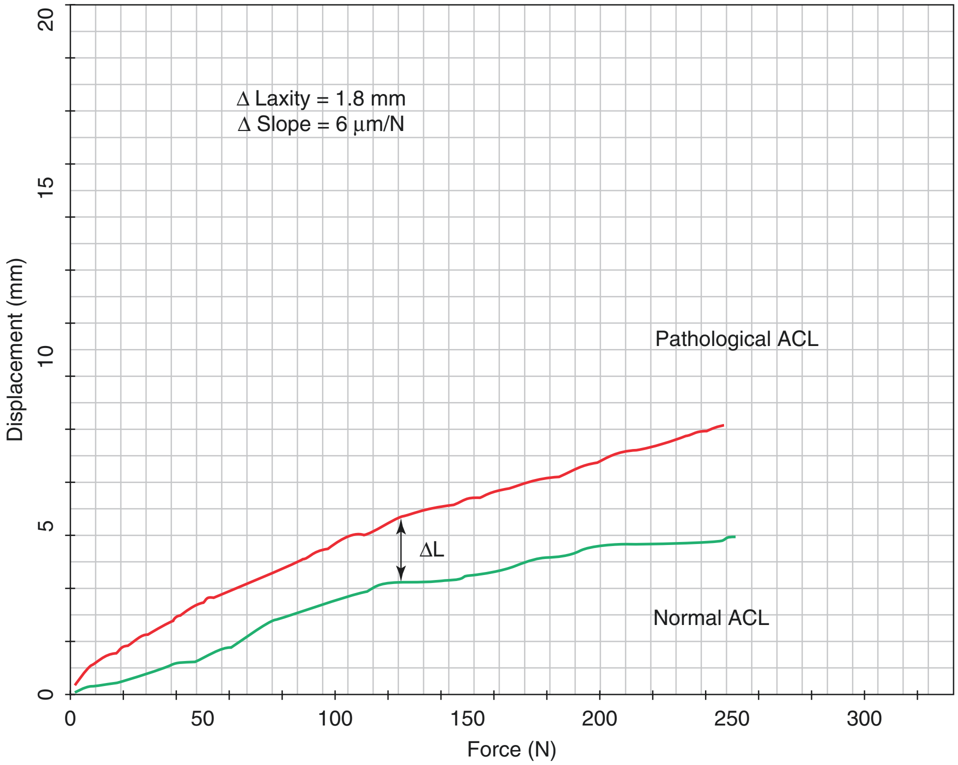

Fig. 38.5 Typical force-displacement curve obtained with the GNRB® in the healthy (*green*) and injured (*red*) knee of an ACL-injured patient with a partial tear (anteromedial bundle)

is determined with the help of a calibration cage. This tridimensional technique has a precision of 0.1 mm [96] and has the advantage not to be influenced by skin movement artefacts [95]. It is more discriminant than the KT-1000® in the postoperative follow-up of ACL patients. The KT-1000® indeed reported lower side-to-side differences than the RSA thus probably overestimating the stabilisation brought by the reconstruction of the ACL [42].

38.1.1.5 Telos Stress Device® (Telos GmbH, Hungen-Obbornhofen, Germany) (Fig. 38.6)

The patient is lying on the side to study anterior knee laxity and supine to assess varus-valgus. The tested leg is placed within two fixed bars inducing 25° of knee flexion. An anterior force is applied at the proximal posterior part of the shank. A dynamometer displays the amount of applied force: 9 or 15 kg, and a lateral radiograph

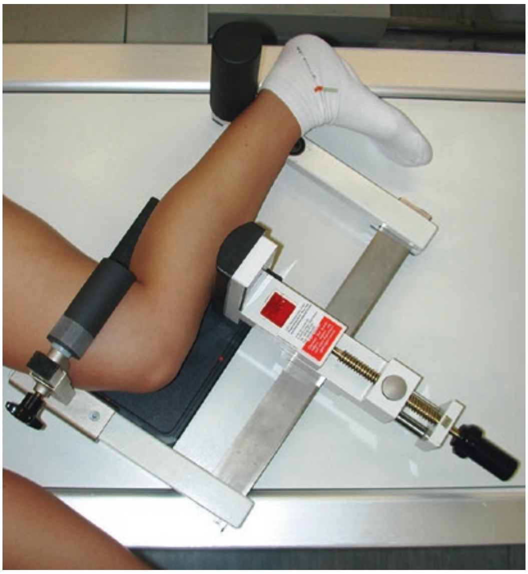

Fig. 38.6 Knee laxity measurements with the Telos Stress Device®. On the picture, analysis of posterior knee laxity at 90° of knee flexion

is realised in this constraint position. Anterior displacement is represented by the distance of two parallel lines: the first line is tangent to the posterior corner of the medial condyle and perpendicular to both tibial plateau; the second is tangent to the posterior border of the medial tibial plateau and perpendicular to both tibial plateau. The distance between both lines is measured in millimetres by the radiologist. Sensitivity of the Telos® is inferior to the KT-1000® (72 % for Telos®; 91 % for KT-1000®) [16]. As such, some authors do not recommend the use of the Telos in the diagnosis and follow-up of ACL injuries [91].

38.1.1.6 Lerat's Method [50]

Lerat's method is easy to use and inexpensive. The patient is lying supine with the hips at the border of a radiological table. The knee is placed on an adapted support inducing 20° of knee flexion. A mass of 9 kg is attached to the patient's thigh above his patella to induce a posterior translation of the femur compared to the tibia. This technique is reliable (intra-tester ICC > 0.9) [51]. The method allows for an individual evaluation of the anterior displacement for the medial and lateral tibial plateau [51]. This method has been reported to be less sensitive than the Telos® or the GNRB® to detect the different types of ACL remnants [13].

38.1.2 Rotational Laxity Measurements

First attempts to measure rotational knee laxity were made in the beginning of the 1980s [48, 59, 67]. Much more complex than anterior knee laxity measurements, rotational knee laxity measurements are not yet used in the daily clinical practice and are still at an experimental stage. In ACL injuries, internal rotation is of main interest even if both internal and external rotations are usually measured. Rotational knee laxity is highly influenced by the patient's position and by the location of rotation measurement. Knee rotation is higher if the knee is flexed at 90° compared to 20° and if the hip is extended compared to flexed at 90° [84]. In ACL injuries, it is usually advised to evaluate patients at 30° of knee flexion. Cadaver studies indeed revealed that the increase in rotation induced by the ACL tear is not detectable anymore above this degree of knee flexion [7, 83, 106]. Regarding the location of the measure of rotation, if the rotation angle is measured at the foot, the tibiofemoral rotation will be overestimated [3]. Foot rotation can represent up to two-thirds of the final measure [84]. To avoid these artefacts, some devices use electromagnetic sensors placed on the tibia [3], which is the most precise method, or assure a good fixation of the ankle and foot (Rotam).

38.1.2.1 Rottometer® [4]

The patient is sitting on a modified chair with knees and hips flexed to 90°. To target tibiofemoral rotation, the thigh is fixed above the knee with clamps. Two screws at the calcaneus and four screws placed at the medial and lateral malleoli fix the ankle. Rotation is measured at the foot with a graduated protractor. A comparative study between the Rottometer® with the RSA technique showed a systematic overestimation of knee rotation which increases with the applied torque [4]. Inter-rater ICC of the Rottometer® reached from 0.69 for a torque of 9 Nm and a knee flexed at 30° [6].

38.1.2.2 Rotameter® [55]

Two prototypes of the Rotameter exist. In both versions, the subject is lying prone to reproduce the dial test position. Thighs are fixed in half cones with two Velcro® strap bands. Hips are extended and knees flexed at 30°. The subject is wearing boots (home-made boot in the first version and ski boots of appropriate size in the second version). They are attached to the handle bar that allows both applying the torque and measuring the degree of rotation. In vivo, inter-rater ICC for the first version of the device has been reported to be greater than 0.88 [56]. A cadaver study comparing the Rotameter with a navigation system showed that the Rotameter overestimated up to 5, 15 and 25° the total range of rotation at 5, 10 and 15 Nm, respectively, but was highly correlated to the navigation system [54, 55].

38.1.2.3 Rotam (Genourob, Laval, France) [77] (Fig. 38.7)

The Rotam is currently under development. It measures knee internal and external rotation induced by a motorised torque between 3 and 10 Nm. The lower limb lies on a composite thermoformed support inducing 30° of knee flexion. The thigh is fixed with a strap and the clamping force is monitored. Foot and ankles are fixed together with two straps into a custom-made boot, which immobilised them with the tibia. The starting position of the knee requires the patella to be at the highest, vertical position. The boot is adjusted to the patient's natural position (usually slightly in external rotation) and calibrated to avoid any constraint on the boot sensors. All internal and external measurements are taken from this neutral position with the help of a gyroscope (precision: 0.1°). Data are acquired continuously, usually under a torque of 5 Nm, to reproduce the torque/displacement curve and calculate the side-to-side differences (Fig. 38.8).

38.1.2.4 Device Presented by Branch et al. [17]

This device is motorised with the patient lying supine with knees flexed at 25°. Femur and patella are stabilised with clamps. The ankle is stabilised in pronation and dorsiflexion to limit its rotation during the test. This device is adjustable to the natural frontal plane leg alignment. Rotation is measured at the foot with an inclinometer. The authors showed that only 49 % of the rotation measured at the foot corresponded to the tibiofemoral rotation [17]. ICC for total range of rotation reached 0.97, but was not evaluated for internal and external rotation separately [17].

38.1.2.5 Rotational Measurement Device [2]

This device consists of three parts: a femoral clamp and a tibial splint to which are fixed inclinometers to measure rotation and a boot with a torque wrench. The rotational measurement device allows for a better evaluation of femorotibial rotation compared to a system which measures the angle of rotation at the foot. The latter option multiplies by three the observed values. The device only showed slightly increased values compared to direct measurements at the tibia with electromagnetic sensors [2].

38.1.2.6 Vermont Knee Laxity Device® [98]

The Vermont Knee Laxity Device® measures anterior, rotational and varus-valgus laxity. The subject is lying supine with knees flexed at 20° and hips at 10°. The thighs are fixed with clamps at the femoral epicondyles. The angle of rotation is measured on the tibia through electromagnetic

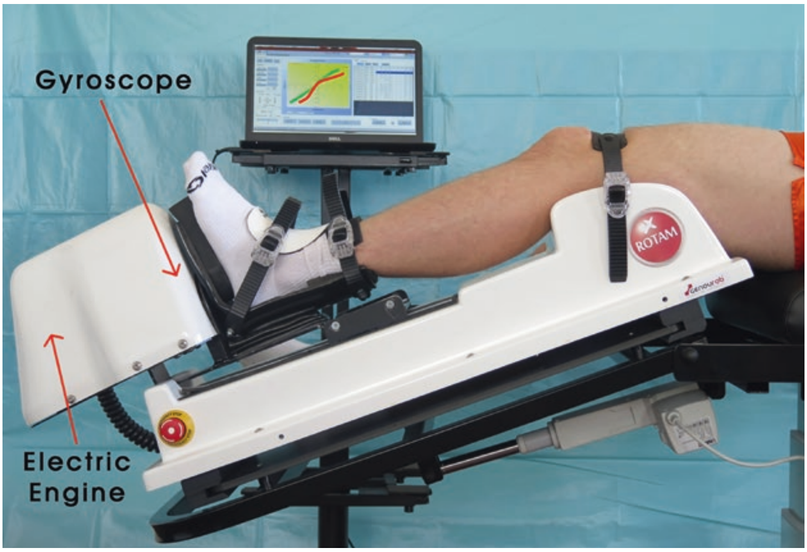

Fig. 38.7 The Rotam: the torque application is motorised, and the rotation is acquired with the help of a gyroscope

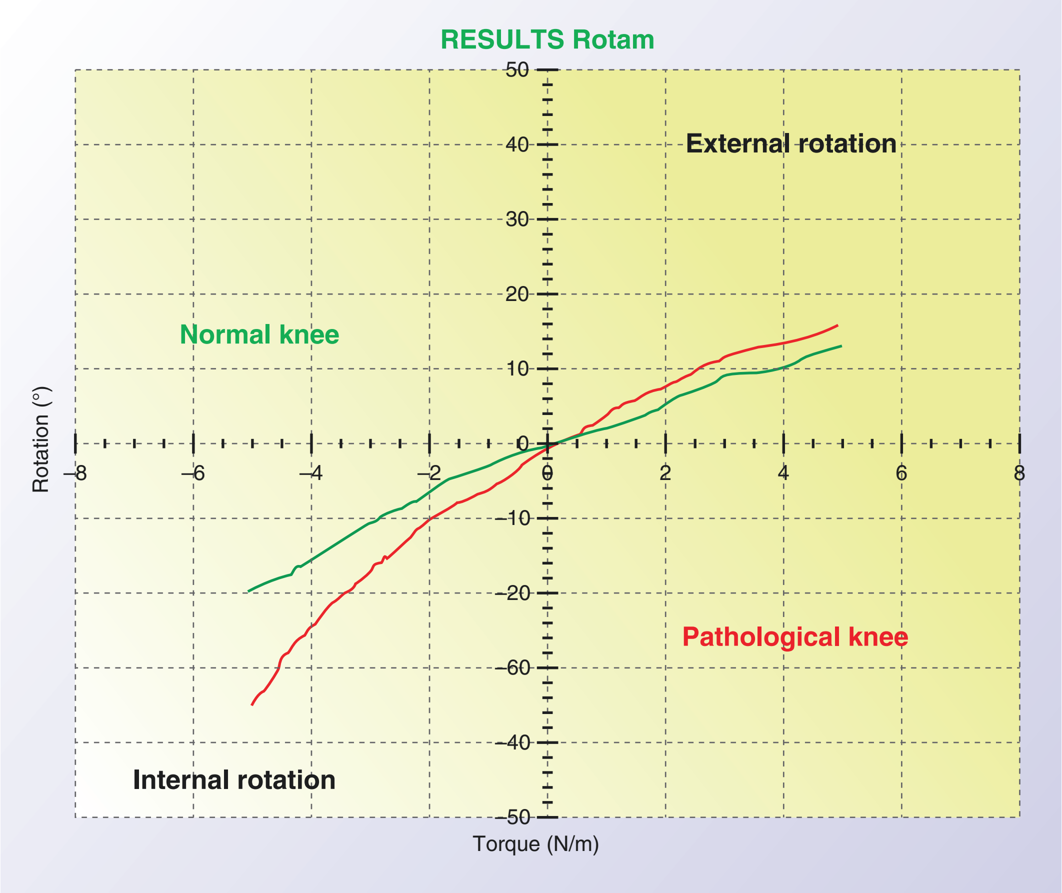

Fig. 38.8 Typical torque-displacement curve obtained with the Rotam before (*green*) and after section of both anterior and anterolateral ligaments (*red*)

sensors. The ICC is above 0.86 for internal, external and total range of rotation [89]. Ninety-five per cent CI of the absolute measurement errors were evaluated to reach 5–7° for internal and external rotation, but was not reported for anterior displacement [89].

38.1.3 Physiological Knee Laxity and Its Role for ACL Injuries

Physiological knee laxity represents the amount of laxity which is considered to lie within the "normal" range. It does not represent knee range of motion, and hence does not include the recurvatum knee in hyperextension, which is often cited in the context of ACL injuries and hyperlaxity [99]. Although limited data are available comparing recurvatum and laxity, both seem to be weakly correlated [53].

Physiological laxity has been more extensively studied due to the recent development of specific arthrometers with improved measurement characteristics. Nevertheless, validity, precision and reference values from a control population are seldom reported, and the results from one device should not be generalised and applied to another one. Still, these aspects are critical, since they allow for an evaluation of the clinical significance of a particular laxity measurement. Thus, ideally every arthrometer should have its own reference values.

Knee laxity is specific to every individual. Based on anterior laxity measurements with the

KT-1000®, values between 1.5 and 14 mm have been reported in the literature in healthy subjects, while up to 21 mm has been measured in healthy contralateral knees of ACL-injured patients and up to 29 mm in patients after ACL injury [81]. Thus, anterior laxity in the contralateral knees of ACL-injured patients on average is greater than the laxity of healthy control individuals [99, 105]. These results suggest that increased physiological laxity could be a risk factor for ACL injuries. The same holds true for rotational knee laxity, which seem to play a similar role in this regard [17, 62].

Physiological knee laxity is influenced by several parameters, which makes it more difficult to establish reference values. The characteristic which is the most frequently discussed in the literature is sex, since women have higher laxity in general compared to men. However, some studies do not confirm this observation, reporting differences of less than 0.3 mm [78, 82], while others do, but based on differences of less than 1.5 mm [74, 99, 108]. One study described a difference of 2.5 mm between men and women [90]. Since the measurement precision of the arthrometers used is rarely reported, the question remains open. On the other hand, sex differences regarding rotational laxity are less controversial [5, 17, 40, 61, 71]. It has been shown that women have up to 40 % higher knee rotation compared to men [61, 71], which could represent a risk factor for the higher ACL injury incidence in women.

Other parameters have been shown to influence physiological knee laxity. Body mass seems to have a considerable impact on rotational laxity [61, 85]. Age can also influence the results, with the paediatric population showing generally greater knee laxity [12, 27, 38]. Similar observations have been made regarding rotational laxity [12]. Knee laxity develops during knee maturation and stabilises around 14 years for girls and around 16 years for boys [12, 27, 38]. No difference has been observed in the paediatric population between girls and boys [12, 27]. As regards the changes in knee laxity at adult age, only limited and inconsistent data exist in the literature [5, 85].

Another factor, which could have an influence on the physiological knee laxity, is the menstrual cycle, but its role on the ACL injury risk has not been clearly established [86, 87]. Lower leg alignment has also been considered to impact on laxity [85, 88] as well as sport activity that increases ACL laxity, while rest decreases it [23]. The team of Shultz et al. [85] has studied combined anterior, rotational and varus-valgus laxity, as well as recurvatum knee. They have shown that healthy individuals with increased frontal and transverse plane laxity tend to have lower values for body mass index, femoral length and muscle force and are generally younger. In this population, increased sagittal laxity was correlated with greater hip anteversion and was inversely proportional to navicular height. Thus, it seems possible to establish knee laxity profiles. Since the different laxity types (sagittal and rotational) are weakly correlated [90], they provide complementary information and should allow to establish more detailed individual knee laxity profiles.

Even though the influence of physiological knee laxity on knee function has not been clearly established, several indicators suggest that it could be related to ACL injury risk and that it could even determine the outcome of ACL reconstructive surgery [18, 43, 44]. However, more data are required to confirm these preliminary conclusions. Recent progress in the area of knee laxity measurements suggests that future multidirectional evaluations will provide complementary information which will allow to establish individual profiles of the static knee laxity envelope.

38.1.4 Laximetry for the Diagnosis of ACL Ruptures

Laxity evaluation in the acute state can be negatively influenced by haemarthrosis, pain and insufficient relaxation of the patient. A proper diagnostic evaluation of knee laxity is thus preferably performed days or weeks following the accident in a non-swollen and non-painful knee. The diagnosis is based on the side-to-side difference between the injured and the healthy knee. Laxity differences as scored with the objective IKDC (International Knee Documentation

Table 38.1 Laxity evaluation as presented in the IKDC knee examination form

	A (normal)	B (nearly normal)	C (abnormal)	D (severely abnormal)
Lachman; 134 N	<3 mm	3–5 mm (+)	6–10 mm (++)	>10 mm (+++)
Lachman; manual maximal anterior endpoint	<3 mm	3–5 mm	6–10 mm	>10 mm

Committee) score are illustrated in Table 38.1. It represents the global reference to describe objective knee function after injury or surgery. Since its last update, this classification has never been questioned, although the surgical procedures for ACL reconstruction have changed over the years. For example, the laxities described under C or D have become rare in everyday clinical practice, and the reference laxity measurements – initially defined by the KT 1000® – are not necessarily valid for other arthrometers. However, it is generally accepted that a laxity difference of 3 mm at an applied anterior force of 134 N (KT-1000®, GNRB®) or a difference in the laxity slope greater than 10 μm/N reflects a complete ACL lesion (GNRB®) [49]. Based on the Telos system, the threshold of laxity difference at 15 kg is however 5 mm, yielding a sensitivity of 81 % and a specificity of 82 %. As well, with the Rolimeter, a similar threshold leads to a sensitivity of 67.5 % and a specificity of 84 % [70].

Currently, the instrumented diagnosis of ACL injury is essentially based on anterior knee laxity. However, the combination of anterior and rotational laxity measurements could increase sensitivity. Regarding rotational knee laxity, there is not yet a consensus concerning the laxity difference threshold to define an ACL injury. A cadaveric study based on 24 healthy knees in which the ACL ligament was sectioned revealed an increase of 3.6 ± 1.2° in internal rotation when applying a torque of 5 Nm (Robert H, personal communication, 2015). An older clinical study on patients with chronic ACL lesions showed that medial tibial rotation of the injured knee was 3.0 ± 6.6° using a torque of 10 Nm, the knee being in 20° flexion, compared to the healthy side [58]. These preliminary results suggest that side-to-side laxity difference may be weak, which highlights even more the need for accurate and reproducible arthrometers to detect ACL injuries.

Ideally, the best diagnostic capacity is achieved by choosing a detection threshold, which provides the highest possible sensitivity (capacity of detecting an ACL rupture) while at the same time yielding the highest specificity (capacity of detecting a healthy knee). By privileging the sensitivity, it is possible to detect a greater proportion of ACL injuries, but this will decrease the specificity, which will yield more false-positive cases. Another possibility is to choose a detection threshold, which optimises the number of correctly classified patients and healthy control subjects.

The studies, which have investigated the diagnostic capacity of arthrometers, have often included patients with complete ACL lesions. However, this does not reflect the clinical reality, because many ACL lesions are partial ruptures. To evaluate the true diagnostic capacity of an arthrometer, it is therefore preferable to consider all kinds of ACL lesions and to determine if different types can be identified prior to surgery.

Several subtypes of ACL lesions have been described in the literature. Based on arthroscopic classification, it is possible to distinguish lesions of a single bundle (the anteromedial bundle being more often concerned than the posterolateral one) with or without a functional remnant, complete lesions with total resorption of the ligament or with a healed remnant on the notch or the PCL [70]. These different scenarios can influence the translational or rotational side-to-side laxity difference [13, 21, 49, 66, 69]. Those lesions where the ligament has totally disappeared are the easiest to diagnose: they are frequently observed in patients with a long-standing lesion, are more often associated with meniscal lesions and present greater side-to-side laxity differences. A second group that can be identified concerns patients with a ligament remnant healed on the PCL, with a laxity difference close to the one of complete ruptures. Those lesions with conservation of the posterolateral bundle are generally more stable anteriorly than the previously described. This is in accordance with the fact that the anteromedial bundle restraints chiefly anterior translation. Those lesions with a healing on the notch pattern are the most stable ones [69].

There is more to the complexity of ACL injuries than the different types of lesions described in the previous paragraph. From a clinical point of view, only 40 % [34] of all cases are isolated ACL lesions. Anteromedial and anterolateral lesions likely influence laxity measurements, but their precise role has not yet been studied in detail. A cadaveric study on 24 healthy knees has revealed that, after a complete section of the ACL, a section of the anterolateral structures increased tibial rotation by 6.4 ± 2° when applying a torque of 5 Nm (Robert H.: personal communication). Therefore, it is recommended to take into account previous and concomitant lesions when interpreting the laxity measurements to avoid false positives. For example, a lesion of the collateral ligaments could influence tibial rotation, and a lesion of the lateral meniscus could modify the pivot-shift test [64]. A medial meniscus lesion could modify anterior tibial displacement, due to its stabilising role in ACL ruptures [64, 94].

38.1.5 Laxity Measurements After ACL Reconstruction

ACL reconstructive surgery aims to restore knee laxity, preferably in all directions. Knee laxity measurements after ACL reconstruction allow the surgeon to detect a graft laxity or a recurrent injury. However, if the contralateral knee has been injured or reconstructed, it is no longer possible to use their measurements as a valid reference value.

Numerous studies reported knee laxity measurements at a specific time point after ACL reconstruction. Their conclusions are difficult to generalise, due to the diversity of surgical techniques (single or double bundle), graft types, fixations, associated injuries, rehabilitation approaches, but also the measurement techniques.

Laxity measurements have often been used to compare the outcome of different surgical techniques. For most, the conclusions are not final. Many studies have shown no difference in anterior laxity after surgical reconstruction between a bone-patellar tendon-bone (BPTB) and a semitendinosus (ST) autograft, be it 2 [36, 37] or even 7 years after surgery [1]. These results have been confirmed in a systematic literature review [92]. However, two meta-analyses comparing the two graft types have found that a side-to-side laxity difference superior to 3 mm was less frequent with BTPB compared to ST grafts [29, 33]. Knee laxity results after an allograft also show controversial results. While some authors report similar outcome than for autografts [9, 31, 57], others suggest that they may be inferior [47].

One of the most discussed topics in the literature is the comparison of reconstructive ACL surgery based on a double-bundle versus a single-bundle technique. Branch et al. [18] concluded that the double-bundle reconstruction leads to greater knee stability than the single-bundle technique both for anterior laxity (1.1 mm; 95 % CI: 0.8–1.5 mm versus 2.2 mm; 95 % CI: 1.7–2.7 mm) and rotational laxity (absolute differences: 2.1°; 95 % CI: 1.6–2.6° versus 4.7°; 95 % CI: 3.6–5.8°). Many meta-analyses and systematic reviews have been published in recent years [46, 52, 60, 97, 100, 107]. The results contradictory in general, but the double-bundle technique seems to be superior in terms of sagittal and rotational stability [52, 97, 100, 107]. A detailed analysis of each of them would be beyond the scope of this chapter. Furthermore, associated lesions and their treatment have been rarely investigated, although it has been shown that a medial meniscectomy modifies the side-to-side laxity difference [64, 76]. The same conclusion holds true for the anterolateral capsule of the knee [19].

There is relatively little information about the prospective follow-up of graft laxity over time following ACL reconstructive surgery. It has been shown that a graft can be stretch after surgery, with a change in the side-to-side laxity difference from −2.1 mm initially to +2.3 mm 1 year later [32]. Repeated laximetry measurements during the first year can allow the surgeon to evaluate graft changes and possibly modify the rehabilitation accordingly. Increasing postsurgical knee laxity could be caused by rehabilitation-induced overload or poor positioning of the graft [75].

The long-term post-operative changes of rotational laxity have not yet been studied. Currently, patient follow-up after ACL surgery is essentially based on manual clinical tests. More efforts have to be done to follow these patients based on regular arthrometric recordings to quantify the changes of knee laxity and the ligamentisation process of the graft.

Conclusion

Since their development in the 1970s and 1980s, the different laximetry techniques have proved useful to complete the preoperative diagnosis and to control the postsurgical outcome. The quantification of sagittal side-to-side difference is an integral part of the IKDC score, the internationally most recognised score to evaluate knee function. However, arthrometric laximetry is very complex and does not merely represent sagittal knee laxity. Some precautions are warranted:

- Sagittal laxity measurements in current publications do not necessarily correspond to those reported some decades ago, because surgery is performed in the acute or subacute setting much more commonly now.
- There is no international consensus on the methods and the instruments used. Yesterday's standard arthrometers, the KT 1000® or the KT 2000®, are no longer in production. Several alternatives are currently available, but they show varying degrees of correlation with the devices used in the past.
- A better understanding of the functional anatomy of the knee joint, especially of the ACL, has focused the predominant discussion around surgical techniques not only on the stabilisation of the knee in the sagittal plane but also in other directions, especially regarding rotation. This opens up a whole new field of laxity measurements. There are currently new arthrometers in development, which allow both for sagittal, and rotational laxity evaluations, or both at the same time, combined or not with dynamic movements or imagery.
- Arthrometry has improved the diagnosis of ACL injuries and their surgical treatments while at the same time allowing the detection of pathological laxity with greater precision. However, the knowledge regarding physiological laxity of the knee remains insufficient. Future studies should evaluate physiological laxity differences related to age, body mass and sex. As well, information about generalised laxity and knee recurvatum may change the surgical decision algorithm.
- Finally, there is still a lack of information regarding post-operative laxity and its changes over time. Except for a few studies that analysed the effect of different surgical techniques at a given moment in time, there are no longitudinal results about the laxity of operated knees over time.

In summary, knee laxity measurements can be used as part of the post-surgery follow-up after ACL reconstruction. It is currently not clear if static or dynamic evaluations are preferred. The former do not accurately reflect the dynamic properties of the knee joint envelope [15], while the latter are technically complex and difficult to quantify. Considering the recent development of arthrometers and measurement procedures and the improved understanding of the ligamentous characteristics of the knee joint in normal and pathological conditions, knee laxity measurements have great potential for applications in the era of personalised medicine and for future individualised follow-up after ACL injury and treatment [8, 39].

References

1. Ahlden M, Kartus J, Ejerhed L, Karlsson J, Sernert N (2009) Knee laxity measurements after anterior cruciate ligament reconstruction, using either bone-patellar-tendon-bone or hamstring tendon autografts, with special emphasis on comparison over time.

Knee Surg Sports Traumatol Arthrosc 17(9):1117–1124

2. Alam M, Bull AM, Thomas R, Amis AA (2013) A clinical device for measuring internal-external rotational laxity of the knee. Am J Sports Med 41(1):87–94
3. Alam M, Bull AM, Thomas RD, Amis AA (2011) Measurement of rotational laxity of the knee: in vitro comparison of accuracy between the tibia, overlying skin, and foot. Am J Sports Med 39(12):2575–2581
4. Almquist PO, Arnbjornsson A, Zatterstrom R, Ryd L, Ekdahl C, Friden T (2002) Evaluation of an external device measuring knee joint rotation: an in vivo study with simultaneous Roentgen stereometric analysis. J Orthop Res 20(3):427–432
5. Almquist PO, Ekdahl C, Isberg PE, Friden T (2013) Knee rotation in healthy individuals related to age and gender. J Orthop Res 31(1):23–28
6. Almquist PO, Ekdahl C, Isberg PE, Friden T (2011) Measurements of knee rotation-reliability of an external device in vivo. BMC Musculoskelet Disord 12:291
7. Andersen HN, Dyhre-Poulsen P (1997) The anterior cruciate ligament does play a role in controlling axial rotation in the knee. Knee Surg Sports Traumatol Arthrosc 5(3):145–149
8. Araujo PH, Kfuri Junior M, Ohashi B, Hoshino Y, Zaffagnini S, Samuelsson K et al (2014) Individualized ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 22(9):1966–1975
9. Bach BR Jr, Aadalen KJ, Dennis MG, Carreira DS, Bojchuk J, Hayden JK et al (2005) Primary anterior cruciate ligament reconstruction using fresh-frozen, nonirradiated patellar tendon allograft: minimum 2-year follow-up. Am J Sports Med 33(2):284–292
10. Balasch H, Schiller M, Friebel H, Hoffmann F (1999) Evaluation of anterior knee joint instability with the rolimeter a test in comparison with manual assessment and measuring with the KT-1000 arthrometer. Knee Surg Sports Traumatol Arthrosc 7(4):204–208
11. Ballantyne BT, French AK, Heimsoth SL, Kachingwe AF, Lee JB, Soderberg GL (1995) Influence of examiner experience and gender on interrater reliability of KT-1000 arthrometer measurements. Phys Ther 75(10):898–906
12. Baxter MP (1988) Assessment of normal pediatric knee ligament laxity using the genucom. J Pediatr Orthop 8(5):546–550
13. Beldame J, Mouchel S, Bertiaux S, Adam JM, Mouilhade F, Roussignol X et al (2012) Anterior knee laxity measurement: comparison of passive stress radiographs Telos((R)) and "Lerat", and GNRB((R)) arthrometer. Orthop Traumatol Surg Res 98(7):744–750
14. Berry J, Kramer K, Binkley J, Binkley GA, Stratford P, Hunter S et al (1999) Error estimates in novice and expert raters for the KT-1000 arthrometer. J Orthop Sports Phys Ther 29(1):49–55
15. Bignozzi S, Zaffagnini S, Lopomo N, Fu F, Irrgang J, Marcacci M (2010) Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18(1):37–42
16. Boyer P, Djian P, Christel P, Paoletti X, Degeorges R (2004) Reliability of the KT-1000 arthrometer (medmetric) for measuring anterior knee laxity: comparison with telos in 147 knees. Rev Chir Orthop Reparatrice Appar Mot 90(8):757–764
17. Branch TP, Browne JE, Campbell JD, Siebold R, Freedberg HI, Arendt EA et al (2010) Rotational laxity greater in patients with contralateral anterior cruciate ligament injury than healthy volunteers. Knee Surg Sports Traumatol Arthrosc 18(10):1379–1384
18. Branch TP, Siebold R, Freedberg HI, Jacobs CA (2011) Double-bundle ACL reconstruction demonstrated superior clinical stability to single-bundle ACL reconstruction: a matched-pairs analysis of instrumented tests of tibial anterior translation and internal rotation laxity. Knee Surg Sports Traumatol Arthrosc 19(3):432–440
19. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J (2013) Anatomy of the anterolateral ligament of the knee. J Anat 223(4):321–328
20. Collette M, Courville J, Forton M, Gagniere B (2012) Objective evaluation of anterior knee laxity; comparison of the KT-1000 and GNRB(R) arthrometers. Knee Surg Sports Traumatol Arthrosc 20(11):2233–2238
21. Crain EH, Fithian DC, Paxton EW, Luetzow WF (2005) Variation in anterior cruciate ligament scar pattern: does the scar pattern affect anterior laxity in anterior cruciate ligament-deficient knees? Arthroscopy 21(1):19–24
22. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R (1985) Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am 67(5):720–726
23. Dargel J, Gotter M, Mader K, Pennig D, Koebke J, Schmidt-Wiethoff R (2007) Biomechanics of the anterior cruciate ligament and implications for surgical reconstruction. Strateg Trauma Limb Reconstr 2(1):1–12
24. Di Iorio A, Carnesecchi O, Philippot R, Farizon F (2014) Multiscale analysis of anterior cruciate ruptures: prospective study of 49 cases. Orthop Traumatol Surg Res 100(7):751–754
25. Feller J, Hoser C, Webster K (2000) EMG biofeedback assisted KT-1000 evaluation of anterior tibial displacement. Knee Surg Sports Traumatol Arthrosc 8(3):132–136
26. Fiebert I, Gresley J, Hoffman S, Kunkel K (1994) Comparative measurements of anterior tibial translation using the KT-1000 knee arthrometer with the leg in neutral, internal rotation, and external rotation. J Orthop Sports Phys Ther 19(6):331–334
27. Flynn JM, Mackenzie W, Kolstad K, Sandifer E, Jawad AF, Galinat B (2000) Objective evaluation of knee laxity in children. J Pediatr Orthop 20(2):259–263
28. Fowler PJ, Lubliner JA (1989) The predictive value of five clinical signs in the evaluation of meniscal pathology. Arthroscopy 5(3):184–186
29. Freedman KB, D'Amato MJ, Nedeff DD, Kaz A, Bach BR Jr (2003) Arthroscopic anterior cruciate

ligament reconstruction: a meta-analysis comparing patellar tendon and hamstring tendon autografts. Am J Sports Med 31(1):2–11

30. Ganko A, Engebretsen L, Ozer H (2000) The rolimeter: a new arthrometer compared with the KT-1000. Knee Surg Sports Traumatol Arthrosc 8(1):36–39
31. Ghodadra NS, Mall NA, Grumet R, Sherman SL, Kirk S, Provencher MT et al (2012) Interval arthrometric comparison of anterior cruciate ligament reconstruction using bone-patellar tendon-bone autograft versus allograft: do grafts attenuate within the first year postoperatively? Am J Sports Med 40(6):1347–1354
32. Giannotti BF, Fanelli GC, Barrett TA, Edson C (1996) The predictive value of intraoperative KT-1000 arthrometer measurements in single incision anterior cruciate ligament reconstruction. Arthroscopy 12(6):660–666
33. Goldblatt JP, Fitzsimmons SE, Balk E, Richmond JC (2005) Reconstruction of the anterior cruciate ligament: meta-analysis of patellar tendon versus hamstring tendon autograft. Arthroscopy 21(7):791–803
34. Granan LP, Bahr R, Lie SA, Engebretsen L (2009) Timing of anterior cruciate ligament reconstructive surgery and risk of cartilage lesions and meniscal tears: a cohort study based on the Norwegian National Knee Ligament Registry. Am J Sports Med 37(5):955–961
35. Hanten WP, Pace MB (1987) Reliability of measuring anterior laxity of the knee joint using a knee ligament arthrometer. Phys Ther 67(3):357–359
36. Harter RA, Osternig LR, Singer KM (1989) Instrumented Lachman tests for the evaluation of anterior laxity after reconstruction of the anterior cruciate ligament. J Bone Joint Surg 71(7):975–983
37. Harter RA, Osternig LR, Singer KM, James SL, Larson RL, Jones DC (1988) Long-term evaluation of knee stability and function following surgical reconstruction for anterior cruciate ligament insufficiency. Am J Sports Med 16(5):434–443
38. Hinton RY, Rivera VR, Pautz MJ, Sponseller PD (2008) Ligamentous laxity of the knee during childhood and adolescence. J Pediatr Orthop 28(2):184–187
39. Hofbauer M, Muller B, Murawski CD, Eck CF, Fu FH (2014) The concept of individualized anatomic anterior cruciate ligament (ACL) reconstruction. Knee Surg Sports Traumatol Arthrosc 22(5):979–986
40. Hsu WH, Fisk JA, Yamamoto Y, Debski RE, Woo SL (2006) Differences in torsional joint stiffness of the knee between genders: a human cadaveric study. Am J Sports Med 34(5):765–770
41. Jenny JY, Arndt J, Computer Assisted Orthopaedic S-F (2013) Anterior knee laxity measurement using stress radiographs and the GNRB((R)) system versus intraoperative navigation. Orthop Traumatol Surg Res 99(6 Suppl):S297–S300
42. Jonsson H, Karrholm J, Elmqvist LG (1993) Laxity after cruciate ligament injury in 94 knees. The KT-1000 arthrometer versus roentgen stereophotogrammetry. Acta Orthop Scand 64(5):567–570
43. Kim SJ, Choi DH, Mei Y, Hwang BY (2011) Does physiologic posterolateral laxity influence clinical outcomes of anterior cruciate ligament reconstruction? J Bone Joint Surg Am 93(21):2010–2014
44. Kim SJ, Lee SK, Kim SH, Kim SH, Kim JS, Jung M (2014) Does anterior laxity of the uninjured knee influence clinical outcomes of ACL reconstruction? J Bone Joint Surg Am 96(7):543–548
45. Klouche S, Lefevre N, Cascua S, Herman S, Gerometta A, Bohu Y (2015) Diagnostic value of the GNRB (R) in relation to pressure load for complete ACL tears: a prospective case-control study of 118 subjects. Orthop Traumatol Surg Res 101(3):297–300
46. Kongtharvonskul J, Attia J, Thamakaison S, Kijkunasathian C, Woratanarat P, Thakkinstian A (2013) Clinical outcomes of double- vs single-bundle anterior cruciate ligament reconstruction: a systematic review of randomized control trials. Scand J Med Sci Sports 23(1):1–14
47. Kraeutler MJ, Bravman JT, McCarty EC (2013) Bone–patellar tendon–bone autograft versus allograft in outcomes of anterior cruciate ligament reconstruction: a meta-analysis of 5182 patients. Am J Sports Med 41(10):2439–2448
48. Lane JG, Irby SE, Kaufman K, Rangger C, Daniel DM (1994) The anterior cruciate ligament in controlling axial rotation. An evaluation of its effect. Am J Sports Med 22(2):289–293
49. Lefevre N, Bohu Y, Naouri JF, Klouche S, Herman S (2014) Validity of GNRB(R) arthrometer compared to telos in the assessment of partial anterior cruciate ligament tears. Knee Surg Sports Traumatol Arthrosc 22(2):285–290
50. Lerat JL, Moyen B, Jenny JY, Perrier JP (1993) A comparison of pre-operative evaluation of anterior knee laxity by dynamic X-rays and by the arthrometer KT 1000. Knee Surg Sports Traumatol Arthrosc 1(1):54–59
51. Lerat JL, Moyen BL, Cladiere F, Besse JL, Abidi H (2000) Knee instability after injury to the anterior cruciate ligament. Quantification of the Lachman test. J Bone Joint Surg Br 82(1):42–47
52. Li X, Xu CP, Song JQ, Jiang N, Yu B (2013) Single-bundle versus double-bundle anterior cruciate ligament reconstruction: an up-to-date meta-analysis. Int Orthop 37(2):213–226
53. Lin HC, Lai WH, Shih YF, Chang CM, Lo CY, Hsu HC (2009) Physiological anterior laxity in healthy young females: the effect of knee hyperextension and dominance. Knee Surg Sports Traumatol Arthrosc 17(9):1083–1088
54. Lorbach O, Pape D, Maas S, Zerbe T, Busch L, Kohn D et al (2010) Influence of the anteromedial and posterolateral bundles of the anterior cruciate ligament on external and internal tibiofemoral rotation. Am J Sports Med 38(4):721–727
55. Lorbach O, Wilmes P, Maas S, Zerbe T, Busch L, Kohn D et al (2009) A non-invasive device to objectively measure tibial rotation: verification of the device. Knee Surg Sports Traumatol Arthrosc 17(7):756–762

56. Lorbach O, Wilmes P, Theisen D, Brockmeyer M, Maas S, Kohn D et al (2009) Reliability testing of a new device to measure tibial rotation. Knee Surg Sports Traumatol Arthrosc 17(8):920–926
57. Mariscalco MW, Magnussen RA, Mehta D, Hewett TE, Flanigan DC, Kaeding CC (2014) Autograft versus nonirradiated allograft tissue for anterior cruciate ligament reconstruction: a systematic review. Am J Sports Med 42(2):492–499
58. Markolf KL, Kochan A, Amstutz HC (1984) Measurement of knee stiffness and laxity in patients with documented absence of the anterior cruciate ligament. J Bone Joint Surg Am 66(2):242–252
59. McQuade KJ, Crutcher JP, Sidles JA, Larson RV (1989) Tibial rotation in anterior cruciate deficient knees: an in vitro study. J Orthop Sports Phys Ther 11(4):146–149
60. Meredick RB, Vance KJ, Appleby D, Lubowitz JH (2008) Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis. Am J Sports Med 36(7): 1414–1421
61. Mouton C, Seil R, Agostinis H, Maas S, Theisen D (2012) Influence of individual characteristics on static rotational knee laxity using the Rotameter. Knee Surg Sports Traumatol Arthrosc 20(4):645–651
62. Mouton C, Theisen D, Meyer T, Agostinis H, Nuhrenborger C, Pape D et al (2015) Noninjured knees of patients with noncontact ACL injuries display higher average anterior and internal rotational knee laxity compared with healthy knees of a noninjured population. Am J Sports Med 43(8):1918–1923
63. Muellner T, Bugge W, Johansen S, Holtan C, Engebretsen L (2001) Inter- and intratester comparison of the rolimeter knee tester: effect of tester's experience and the examination technique. Knee Surg Sports Traumatol Arthrosc 9(5):302–306
64. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD (2010) The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 38(8):1591–1597
65. Myrer JW, Schulthies SS, Fellingham GW (1996) Relative and absolute reliability of the KT-2000 arthrometer for uninjured knees: testing at 67, 89, 134, and 178 N and manual maximum forces. Am J Sports Med 24(1):104–108
66. Nakase J, Toratani T, Kosaka M, Ohashi Y, Tsuchiya H (2013) Roles of ACL remnants in knee stability. Knee Surg Sports Traumatol Arthrosc 21(9):2101–2106
67. Nielsen S, Ovesen J, Rasmussen O (1984) The anterior cruciate ligament of the knee: an experimental study of its importance in rotatory knee instability. Arch Orthop Trauma Surg 103(3):170–174
68. Noyes FR, Cummings JF, Grood ES, Walz-Hasselfeld KA, Wroble RR (1991) The diagnosis of knee motion limits, subluxations, and ligament injury. Am J Sports Med 19(2):163–171
69. Panisset JC, Duraffour H, Vasconcelos W, Colombet P, Javois C, Potel JF et al (2008) Clinical, radiological and arthroscopic analysis of the ACL tear. A prospective study of 418 cases. Rev Chir Orthop Reparatrice Appar Mot 94(8 Suppl):362–368
70. Panisset JC, Ntagiopoulos PG, Saggin PR, Dejour D (2012) A comparison of telos stress radiography versus rolimeter in the diagnosis of different patterns of anterior cruciate ligament tears. Orthop Traumatol Surg Res 98(7):751–758
71. Park HS, Wilson NA, Zhang LQ (2008) Gender differences in passive knee biomechanical properties in tibial rotation. J Orthop Res 26(7):937–944
72. Pugh L, Mascarenhas R, Arneja S, Chin PY, Leith JM (2009) Current concepts in instrumented knee-laxity testing. Am J Sports Med 37(1):199–210
73. Robert H, Nouveau S, Gageot S, Gagniere B (2009) A new knee arthrometer, the GNRB: experience in ACL complete and partial tears. Orthop Traumatol Surg Res 95(3):171–176
74. Rozzi SL, Lephart SM, Gear WS, Fu FH (1999) Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. Am J Sports Med 27(3):312–319
75. Rupp S, Muller B, Seil R (2001) Knee laxity after ACL reconstruction with a BPTB graft. Knee Surg Sports Traumatol Arthrosc 9(2):72–76
76. Salmon LJ, Russell VJ, Refshauge K, Kader D, Connolly C, Linklater J et al (2006) Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-year review. Am J Sports Med 34(5):721–732
77. Samson W, Cheze L (2015) An experimental set-up to assess knee stiffness: a pilot study. Comput Methods Biomech Biomed Engin. doi:10.1080/10255842.2015.10696181-2
78. Scerpella TA, Stayer TJ, Makhuli BZ (2005) Ligamentous laxity and non-contact anterior cruciate ligament tears: a gender-based comparison. Orthopedics 28(7):656–660
79. Schuster AJ, McNicholas MJ, Wachtl SW, McGurty DW, Jakob RP (2004) A new mechanical testing device for measuring anteroposterior knee laxity. Am J Sports Med 32(7):1731–1735
80. Sernert N, Helmers J, Kartus C, Ejerhed L, Kartus J (2007) Knee-laxity measurements examined by a left-hand- and a right-hand-dominant physiotherapist, in patients with anterior cruciate ligament injuries and healthy controls. Knee Surg Sports Traumatol Arthrosc 15(10):1181–1186
81. Sernert N, Kartus JT Jr, Ejerhed L, Karlsson J (2004) Right and left knee laxity measurements: a prospective study of patients with anterior cruciate ligament injuries and normal control subjects. Arthroscopy 20(6):564–571
82. Sharma L, Lou C, Felson DT, Dunlop DD, Kirwan-Mellis G, Hayes KW et al (1999) Laxity in healthy and osteoarthritic knees. Arthritis Rheum 42(5): 861–870
83. Shoemaker SC, Markolf KL (1985) Effects of joint load on the stiffness and laxity of ligament-deficient knees. An in vitro study of the anterior cruciate and

medial collateral ligaments. J Bone Joint Surg Am 67(1):136–146

84. Shoemaker SC, Markolf KL (1982) In vivo rotatory knee stability. Ligamentous and muscular contributions. J Bone Joint Surg Am 64(2):208–216
85. Shultz SJ, Dudley WN, Kong Y (2012) Identifying multiplanar knee laxity profiles and associated physical characteristics. J Athl Train 47(2):159–169
86. Shultz SJ, Kirk SE, Johnson ML, Sander TC, Perrin DH (2004) Relationship between sex hormones and anterior knee laxity across the menstrual cycle. Med Sci Sports Exerc 36(7):1165–1174
87. Shultz SJ, Levine BJ, Nguyen AD, Kim H, Montgomery MM, Perrin DH (2010) A comparison of cyclic variations in anterior knee laxity, genu recurvatum, and general joint laxity across the menstrual cycle. J Orthop Res 28(11):1411–1417
88. Shultz SJ, Nguyen AD, Levine BJ (2009) The relationship between lower extremity alignment characteristics and anterior knee joint laxity. Sports Health 1(1):54–60
89. Shultz SJ, Shimokochi Y, Nguyen AD, Schmitz RJ, Beynnon BD, Perrin DH (2007) Measurement of varus-valgus and internal-external rotational knee laxities in vivo – Part I: assessment of measurement reliability and bilateral asymmetry. J Orthop Res 25(8):981–988
90. Shultz SJ, Shimokochi Y, Nguyen AD, Schmitz RJ, Beynnon BD, Perrin DH (2007) Measurement of varus-valgus and internal-external rotational knee laxities in vivo – part II: relationship with anterior-posterior and general joint laxity in males and females. J Orthop Res 25(8):989–996
91. Sorensen OG, Larsen K, Jakobsen BW, Kold S, Hansen TB, Lind M et al (2011) The combination of radiostereometric analysis and the telos stress device results in poor precision for knee laxity measurements after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19(3):355–362
92. Spindler KP, Kuhn JE, Freedman KB, Matthews CE, Dittus RS, Harrell FE (2004) Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring: does It really matter? A systematic review. Am J Sports Med 32(8):1986–1995
93. Stefan Aronson A, Hoist L, Selvik G (1974) An instrument for insertion of radiopaque bone markers. Radiology 113(3):733–734
94. Sullivan D, Levy IM, Sheskier S, Torzilli PA, Warren RF (1984) Medical restrains to anterior-posterior motion of the knee. J Bone Joint Surg 66(6):930–936
95. Tashman S, Anderst W, Kolowich P, Havstad S, Arnoczky S (2004) Kinematics of the ACL-deficient canine knee during gait: serial changes over two years. J Orthop Res 22(5):931–941
96. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983
97. Tiamklang T, Sumanont S, Foocharoen T, Laopaiboon M (2012) Double-bundle versus single-bundle reconstruction for anterior cruciate ligament rupture in adults. Cochrane Database Syst Rev (11):CD008413
98. Uh BS, Beynnon BD, Churchill DL, Haugh LD, Risberg MA, Fleming BC (2001) A new device to measure knee laxity during weightbearing and non-weightbearing conditions. J Orthop Res 19(6):1185–1191
99. Uhorchak JM, Scoville CR, Williams GN, Arciero RA, St Pierre P, Taylor DC (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. Am J Sports Med 31(6):831–842
100. van Eck CF, Kopf S, Irrgang JJ, Blankevoort L, Bhandari M, Fu FH et al (2012) Single-bundle versus double-bundle reconstruction for anterior cruciate ligament rupture: a meta-analysis – does anatomy matter? Arthroscopy 28(3):405–424
101. van Eck CF, Loopik M, van den Bekerom MP, Fu FH, Kerkhoffs GM (2013) Methods to diagnose acute anterior cruciate ligament rupture: a meta-analysis of instrumented knee laxity tests. Knee Surg Sports Traumatol Arthrosc 21(9):1989–1997
102. Vauhnik R, Morrissey MC, Perme MP, Sevsek F, Rugelj D (2014) Inter-rater reliability of the GNRB(R) knee arthrometer. Knee 21(2):541–543
103. Vauhnik R, Perme MP, Barcellona MG, Rugelj D, Morrissey MC, Sevsek F (2013) Robotic knee laxity testing: reliability and normative data. Knee 20(4):250–255
104. Wiertsema SH, van Hooff HJ, Migchelsen LA, Steultjens MP (2008) Reliability of the KT1000 arthrometer and the Lachman test in patients with an ACL rupture. Knee 15(2):107–110
105. Woodford-Rogers B, Cyphert L, Denegar CR (1994) Risk factors for anterior cruciate ligament injury in high school and college athletes. J Athl Train 29(4):343–346
106. Zarins B, Rowe CR, Harris BA, Watkins MP (1983) Rotational motion of the knee. Am J Sports Med 11(3):152–156
107. Zhu Y, Tang RK, Zhao P, Zhu SS, Li YG, Li JB (2013) Double-bundle reconstruction results in superior clinical outcome than single-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc 21(5):1085–1096
108. Zyroul R, Hossain MG, Azura M, Abbas AA, Kamarul T (2014) Knee laxity of Malaysian adults: gender differentials, and association with age and anthropometric measures. Knee 21(2):557–562

39

Instrumental Dynamic Laxity Evaluation: Non-invasive Inertial Sensors

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Fact Boxes

1. For the diagnosis of the ACL (anterior cruciate ligament)-injured and ACL-reconstructed knee, it is necessary to have valid, reliable, and quantitative measures performed by a noninvasive device.
2. There is an overall agreement that a dynamic parameter, such as 3D acceleration, should represent the dynamism of the PS phenomenon and can be related with the dynamic instability assessed by the PS test.
3. The current solution represents a valid help for the clinical examination allowing to detect and quantify the grade of a suspected ACL injury.

39.1 Introduction

The most sensitive test to detect a torn anterior cruciate ligament (ACL) is the Lachman test. It measures the anterior-posterior displacement of the femur with respect to the tibia in the sagittal plane [1]. Unfortunately, this test does not evaluate the dynamic laxity. In contrast, pivot shift (PS) test analyzes the knee joint under a dynamic situation and tests both anterior-posterior and rotational laxity [2, 3]. Moreover, the PS test is widely used for objective assessment of the joint laxity in the most common clinical scores for ligament laxity such as the International Knee Documentation Committee score [4]. However, it is well known that the pivot shift test seems to be very subjective and examiner dependent [5]. Quite complex system which needs footplates [6], magnetic resonance imaging [7], markers [8], and robotic technology [9] has been developed during the last years to quantify PS outcome. Also, electromagnetic sensors were dedicated to quantitatively evaluate PS test [10–13]; unfortunately, they present a quite complicated equipment (wires, specific surgical instrumentation, and setup) and costs incompatible with office practice. In particular, Labbe et al. in 2010 [2] found that both acceleration and velocity during PS test could be an indicative parameter for dynamic laxity which is also correlated to clinical grade of PS. Analogously, Hoshino et al. in 2007, 2011, and 2012 [3, 14,

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15] used an electromagnetic device to evaluate PS test acceleration. Even the RSA (Roentgen stereophotogrammetric analysis) resulted to be a very precise system when evaluating in vivo joint motion [16]. The procedure involves insertion of multiple tantalum markers in the tibia as well as the femur bone. Imaging is done with biplane radiographs with a sample rate of up to 300 Hz. To capture significant events during running or jumping, a sample rate of at least 100 Hz is required. DSX (dynamic stereo-X-ray) imaging is a similar but noninvasive method that evolved from RSA. A model-based tracking technique is used to align three-dimensional CT scans with the radiographic image pairs. Disadvantages for RSA as well as DSX include exposure to radiation, high costs, and the need for manual labor-intensive analysis for processing the data. Also MRI (magnetic resonance imaging) has been introduced for the in vivo analysis of knee joint kinematics. Disadvantages are low frame rates, radiations, and restrictions for functional weight-bearing movements. The presence of radiation strongly limits the use of the device, previously reported, for clinical laxity test such as PS test, where the presence of a tester is required. Recently, a software for computer and tablet which quantify anterior translation of the lateral knee compartment during the pivot shift test has been proposed. It is based on the simple image analysis method using the video camera of an iPad [17]. Computer-assisted surgery (CAS) has been used to assess knee kinematics and laxity. It allows the decomposition of the PS and a direct feedback on laxity testing. The technique results to be highly precise; unfortunately, it results to be invasive, limiting the evaluation to the ipsilateral side. The CAS system, also defined as navigation system, is considered the gold standard for knee laxity evaluation. After a long experience in laxity quantification using navigation system, the authors of the present chapter decided to move toward an innovative and noninvasive approach using acceleration signal in order to quantify knee joint dynamic laxity for ACL injury diagnosis. Similar approaches were subsequently followed by different research groups around the world.

39.2 The Importance of an Automatic and Noninvasive Evaluation

ACL tear is one of the most common injuries in sports activity and can affect even less active people [18]. ACL reconstruction is one of the most commonly performed procedures in orthopedics [19]. The significance and role of any grading method lies on its ability to aid in the decision-making process during diagnosis, surgical treatment, and recovery phase after surgery. Moreover, an accurate diagnosis may be beneficial to provide patients with the correct information to help manage their expectations. Making an accurate diagnosis of the laxity grade is a crucial point to choose the appropriate surgical treatment: errors in this practice can lead to inadequate surgical approach that can also worsen the biomechanics of the joint. A surgical procedure that corrects only one aspect of the knee laxity has no chance to restore normal joint physiology. In particular, when it comes to the diagnosis of the ACL-injured and ACL-reconstructed knee, it is necessary to have valid, reliable, and quantitative measures performed by a noninvasive tool. First of all, the quantification of knee laxity level is fundamental for an early diagnosis in order to determine if surgery is required and which one is suitable. Secondly, intraoperatively it is important to quantify the laxity level to immediately evaluate the improvement achieved during the surgery and evaluate the need to perform a secondary restrain procedure. Moreover, during the recovery processes, it is important to follow the laxity recovery in order to verify the healing process. As previously underlined, there is a lack of validated measurement device that can be used to assess dynamic laxity of the knee. Further reliability and validation studies are needful to assess the use of skin-fixed sensors when evaluating dynamic laxity tests such as PS. Reliable methods to measure dynamic laxity in the clinical setting as well as operating room are warranted. For all the previous arguments, the optimal solution should be an automatic, simple, reproducible, convenient, and quantitative evaluation of the PS tests. The current work is based on the hypothesis that a dynamic parameter, such as 3D acceleration, should represent the dynamism of the PS phenomenon and can be related to the dynamic instability assessed by the PS test. The hypothesis is supported by the analysis of the literature that, as previously underlined, considers the velocity as well as the acceleration during PS test a potential indicator of the phenomenon.

39.3 Acceleration to Quantify PS Test: KiRA Device (Orthokey LLC, DE, USA)

KiRA (*Orthokey LLC*, *DE*, *USA*) is a medical device that supports the analysis of knee laxities, providing both real-time graphics and quantitative information about the pivot shift test and in its last version the Lachman test, as well. The diagnosis of anterior cruciate ligament injury is a process that includes a set of complex information to be connected, and often, it is difficult to carry out a choice especially in the case of partial ligament injury. This is especially relevant and critical to professional athletes. Clinical relevance, ability to quantify laxity in different conditions, and validation by comparison with the navigation system of the device have been the subject of previous scientific publications. The device represents a useful aid to the clinical examination allowing to detect and quantify the grade of a suspected ACL injury. Regarding the pivot shift analysis, the functioning device is based on the hypothesis that a dynamic parameter, such as 3D acceleration, should represent the dynamism of the PS phenomenon and can be related to the dynamic instability assessed by the PS test. The hypothesis is supported by the analysis of the literature [20] that, as previously underlined, considers the velocity as well as the acceleration during PS test a potential indicator of the phenomenon. The sensor must be skin fixed on the tibial bone by the provided hypoallergenic strap. The device must be placed between the lateral aspect of the anterior tuberosity and the Gerdy tubercle to achieve an optimal stability and minimize skin artifacts during the maneuver. There is no need to shave or clean the skin. Analogously, any type of contact paste such as gel was used (Fig. 39.1).

Fig. 39.1 Positioning of the sensor during PS analysis

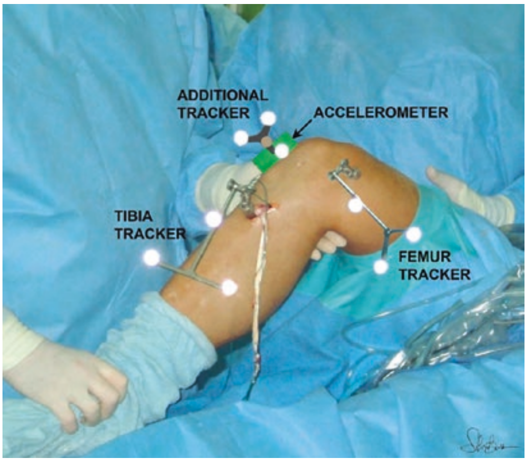
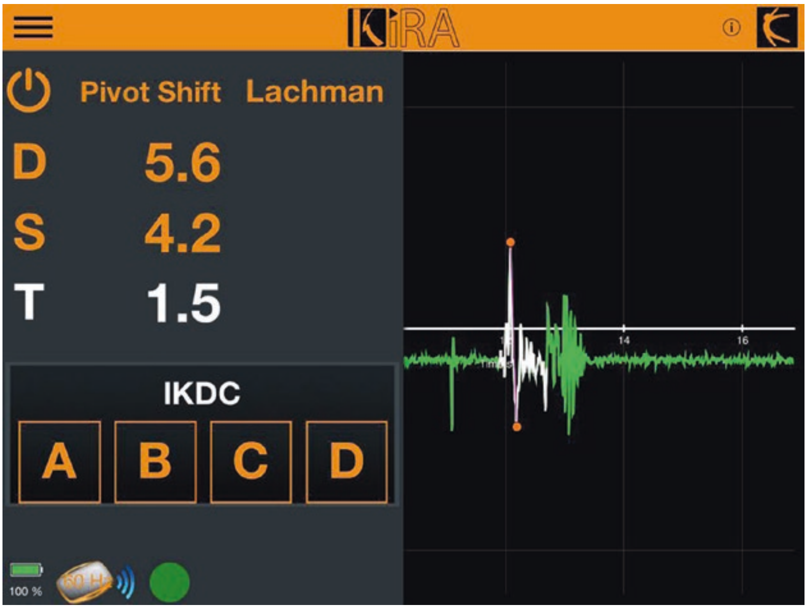


Fig. 39.2 Intraoperative setup: trackers of navigation system and noninvasive device for dynamic laxity evaluation

The device can be also used during the intraoperative dynamic laxity evaluation [21]. For this specific condition, the sensor needs to be enclosed in a specifically developed sterilizable box which will be then skin fixed to the patient. No other modifications are required (Fig. 39.2).

In order to validate the proposed device, different clinical studies have been carried out [21–24]. Compared to these works, it is worth noting that the easiness of using the purposed device does not involve any alteration to the surgical procedure or operative setup when the device is intraoperatively used. It has been specifically designed with material resistant to sterilization



D 5.6
S 4.2
T 1.5

Fig. 39.3 KiRA software interface for pivot shift test quantification (Orthokey LLC, DE, USA). On the *left* part of the screen, there are the acceleration values acquired both on the *left* (*D*) and *right* (*S*) knee joint as well as the difference between them (*T*). On the *right* part, there is whole acquired signal for the left knee

which makes cleaning quick, easy, and complete. The device shows an ergonomics for simplicity of use and easy placement by the surgical team. Even the software has been designed in order to be easily used even by nontechnical personnel, such as the surgeon. The software interface (Fig. 39.3) is simple and intuitive, and this ease of use is demonstrated by the short time needed for learning, which has been proven by using the device even by nonspecifically trained surgeons [25]. The main limitation of the purposed method consisted in the execution way of the maneuver which is manually performed without load control. This limitation is partially compensated by the introduction of a standardized test [15]. Anyway, the high level of intra- and inter-tester repeatability *strengthens* the validity of the purposed method. Even the different interpretations on how to apply and evaluate the PS test among the different surgeons represent a criticality in the definition of an objective evaluation of the test. We also defined a trial study during the Panther Global Summit (Pittsburgh, August 2011), where 12 expert surgeons evaluated the effect of the standardization in the PS maneuver [26]. In such study, the KiRA device was used to quantify the ligament laxity. After watching an instructional video, explaining the PS test, the 12 acceleration curves look similar, whereas during the surgeons' preferred technique, they did not [15].

39.3.1 Discussion

Instrumental dynamic laxity evaluation during pivot shift test, using acceleration sensors, appears to be promising at this time. The development of such technology has made pivot shift more objective. The main problem in evaluating PS test was reported to lay on the complexity of the maneuver which makes it a surgeon-subjective laxity examination [27–31]. The test was described as depending also on the patient ability to relax their muscles during the examination [32]. Given that, there is still a lack of possibility for accurate pivot shift test quantification above all in office practice. The current solution using acceleration sensor made significant contributions to the scientific knowledge on the clinical PS test, introducing a possibility of quantifying the maneuver in a noninvasive fashion. ACL reconstruction is currently the seventh most common surgical procedure in the USA [33], and during the period 2000–2010, the research data in terms of ACL research have more than doubled [34]. A timely and precise diagnosis is certainly the first step to allow a successful recovery of the incident. Even if a careful history, detailed preoperative MRI, and physical examination will always remain fundamental for a complete evaluation, the possibility to perform an instrumented objective and quantitative evaluation of joint laxity represents a need for the orthopedic surgeon dealing with this issue. Using the current device, no anatomical registration phase is required before the data acquisition. The analysis is based on the definition of few simple parameters that are automatically and real time detected by the custom-made software. Moreover, the noninvasiveness of the presented sensor allows evaluating the side-to-side difference in each patient. As the ligament laxity is highly characteristic of each single subject, the comparison between the two joint results is more suitable for an objective diagnosis, deleting the baseline joint laxity [35]. Furthermore, since the PS was proved to be variable and difficult to execute [36–38], even considering the same surgeon and the same patient, the intra-tester repeatability in a controlled setup using the acceleration signal to quantify PS test has been evaluated. The obtained reliability was comparable to the results that the literature reports for static laxity test [38]. As previously reported, part of the validation of the purposed method was performed by the comparison with the navigation system outcome, which is considered the gold standard for intraoperative laxity evaluation. Indeed, for the knee laxity evaluation, navigation systems represent the gold standard. Unfortunately, even if the CAS system allows for a reliable and quantitative evaluation, being highly invasive, a navigation system becomes applicable only during the surgery and excludes the possibility to evaluate the contralateral limb and, clearly, its use in ambulatory practice. In any event, the reproducibility and accuracy of the CAS system for ACL laxity evaluation support its use as the reference gold standard against which other devices should be tested. Further studies will be dedicated to optimize and simplify the developed device making it a universal tool that can be used in the clinical practice to assess clinical outcome after ACL injury and surgery, as well, thus allowing a complete analysis of knee joint laxity, providing information not only on the acceleration reached during the PS test but also quantitative knowledge about translations and rotations. In conclusion, the presented device could assist orthopedic surgeons in the assessment of the potential ACL injury. Quantification of dynamic laxity, following the current method, could help the surgeon in determination of surgical strategies specific for each patient since it is independent from the examiner. It would represent a major breakthrough in the field being the first device with such capability. Moreover, the noninvasiveness of the device guarantees its use during the whole postoperative course and in case of sportive patients offers a concrete possibility to monitor when the dynamic laxity decreases below a threshold which ensures the return to sport in complete safety.

References

1. Oberlander MA, Shalvoy RM, Hughston JC (1993) The accuracy of the clinical knee examination documented by arthroscopy. A prospective study. Am J Sports Med 21(6):773–778
2. Bull AMJ, Earnshaw PH, Smith A, Katchburian MV, Hassan ANA, Amis AA (2002) Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br 84(7):1075–1081
3. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 35(7):1098–1104
4. Hefti F, Müller W, Jakob RP, Stäubli HU (1993) Evaluation of knee ligament injuries with the IKDC form. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 1(3–4):226–234
5. Noyes FR, Grood ES, Cummings JF, Wroble RR (1991) An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. Am J Sports Med 19(2):148–155
6. Amis A, Bull A, Lie D (2005) Biomechanics of rotational instability and anatomic anterior cruciate ligament reconstruction. Operative Techniques in Orthopaedics 15(1):29–35
7. Tashiro Y, Okazaki K, Miura H, Matsuda S, Yasunaga T, Hashizume M, Nakanishi Y, Iwamoto Y (2009) Quantitative assessment of rotatory instability after anterior cruciate ligament reconstruction. Am J Sports Med 37(5):909–916

8. Csintalan RP, Ehsan A, McGarry MH, Fithian DF, Lee TQ (2006) Biomechanical and anatomical effects of an external rotational torque applied to the knee: a cadaveric study. Am J Sports Med 34(10):1623–1629
9. Diermann N, Schumacher T, Schanz S, Raschke MJ, Petersen W, Zantop T (2009) Rotational instability of the knee: internal tibial rotation under a simulated pivot shift test. Arch Orthop Trauma Surg 129(3):353–358
10. Amis A, Cuomo P, Rama R, Giron F, Bull A, Rhidian T, Aglietti P (2008) Measurement of knee laxity and pivot-shift kinematics with magnetic sensors. Operative Techniques in Orthopaedics 18(3):196–203
11. Kuroda R, Hoshino Y, Nagamune K, Kubo S, Nishimoto K, Araki D, Yamaguchi M, Yoshiva M, Kurosaka M (2008) Intraoperative measurement of pivot shift by electromagnetic sensors. Operative Techniques in Orthopaedics 18(3):190–195
12. Labbe DR, de Guise JA, Mezghani N, Godbout V, Grimard G, Baillargeon D, Lavigne P, Fernandes J, Ranger P, Hagemeister N (2010) Feature selection using a principal component analysis of the kinematics of the pivot shift phenomenon. J Biomech 43(16):3080–3084
13. Labbe DR, de Guise JA, Godbout V, Grimard G, Baillargeon D, Lavigne P, Fernandes J, Massé V, Ranger P, Hagemeister N (2011) Accounting for velocity of the pivot shift test manoeuvre decreases kinematic variability. Knee 18(2):88–93
14. Hoshino Y, Kuroda R, Nagamune K, Araki D, Kubo S, Yamaguchi M, Kurosaka M (2011) Optimal measurement of clinical rotational test for evaluating anterior cruciate ligament insufficiency. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 20(7):1323–1330
15. Hoshino Y, Araujo P, Ahlden M, Moore CG, Kuroda R, Zaffagnini S, Karlsson J, Fu FH, Musahl V (2012) Standardized pivot shift test improves measurement accuracy. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 20(4):732–736
16. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983
17. Muller B, Hofbauer M, Rahnemai-Azar AA, Wolf M, Araki D, Hoshino Y, Araujo P, Debski RE, Irrgang JJ, Fu FH, Musahl V (2016) Development of computer tablet software for clinical quantification of lateral knee compartment translation during the pivot shift test. Comput Methods Biomech Biomed Eng 19(2):217–228
18. Fu FH, Bennett CH, Lattermann C, Ma CB (1999) Current trends in anterior cruciate ligament reconstruction. Part 1: biology and biomechanics of reconstruction. Am J Sports Med 27(6):821–830
19. Renstrom P, Ljungqvist A, Arendt E, Beynnon B, Fukubayashi T, Garrett W, Georgoulis T, Hewett TE, Johnson R, Krosshaug T, Mandelbaum B, Micheli L, Myklebust G, Roos E, Roos H, Schamasch P, Shultz S, Werner S, Wojtys E, Engebretsen L (2008) Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. Br J Sports Med 42(6):394–412
20. Ishibashi Y, Tsuda E, Yamamoto Y, Tsukada H, Toh S (2009) Navigation evaluation of the pivot-shift phenomenon during double-bundle anterior cruciate ligament reconstruction: is the posterolateral bundle more important? Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 25(5): 488–495
21. Lopomo N, Zaffagnini S, Signorelli C, Bignozzi S, Giordano G, Marcheggiani Muccioli GM, Visani A (2012) An original clinical methodology for non-invasive assessment of pivot-shift test. Comput Methods Biomech Biomed Engin 15(12):1323–1328
22. Zaffagnini S, Lopomo N, Signorelli C, Marcheggiani Muccioli GM, Bonanzinga T, Grassi A, Raggi F, Visani A, Marcacci M (2014) Inertial sensors to quantify the pivot shift test in the treatment of anterior cruciate ligament injury. Joints 2(3):124–129
23. Zaffagnini S, Lopomo N, Signorelli C, Marcheggiani Muccioli GM, Bonanzinga T, Grassi A, Visani A, Marcacci M (2013) Innovative technology for knee laxity evaluation: clinical applicability and reliability of inertial sensors for quantitative analysis of the pivot-shift test. Clin Sports Med 32(1):61–70, Epub 2012 Sep 25. Review
24. Lopomo N, Signorelli C, Bonanzinga T, Marcheggiani Muccioli GM, Visani A, Zaffagnini S (2012) Quantitative assessment of pivot-shift using inertial sensors. Knee Surg Sports Traumatol Arthrosc 20(4):713–717
25. Berruto M, Uboldi F, Gala L, Marelli B, Albisetti W (2013) Is triaxial accelerometer reliable in the evaluation and grading of knee pivot-shift phenomenon? Knee Surg Sports Traumatol Arthrosc Off J ESSKA 21(4):981–985
26. Hoshino Y, Araujo P, Ahlden M, Moore CG, Kuroda R, Zaffagnini S, Karlsson J, Fu FH, Musahl V (2012) Standardized pivot shift test improves measurement accuracy. Knee Surg Sports Traumatol Arthrosc 20(4):732–736
27. Jakob RP, Stäubli HU, Deland JT (1987) Grading the pivot shift. Objective tests with implications for treatment. J Bone Joint Surg Br 69(2):294–299
28. Kuroda R, Hoshino Y, Kubo S, Araki D, Oka S, Nagamune K, Kurosaka M (2012) Similarities and differences of diagnostic manual tests for anterior cruciate ligament insufficiency: a global survey and kinematics assessment. Am J Sports Med 40(1):91–99
29. Noyes FR, Bassett RW, Grood ES, Butler DL (1980) Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. J Bone Joint Surg Am 62(5):687–695, 757
30. Sakai H, Yajima H, Kobayashi N, Kanda T, Hiraoka H, Tamai K, Saotome K (2006) Gravity-assisted pivot-shift test for anterior cruciate ligament injury: a new procedure to detect anterolateral rotatory instability of the knee joint. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 14(1):2–6
31. Slocum DB, James SL, Larson RL, Singer KM (1976 Aug) Clinical test for anterolateral rotary instability of the knee. Clin Orthop (118):63–69

32. Donaldson WF, Warren RF, Wickiewicz T (1985) A comparison of acute anterior cruciate ligament examinations. Initial versus examination under anesthesia. Am J Sports Med 13(1):5–10
33. Fox JA, Pierce M, Bojchuk J, Hayden J, Bush-Joseph CA, Bach BR (2004) Revision anterior cruciate ligament reconstruction with nonirradiated fresh-frozen patellar tendon allograft. Arthrosc J Arthrosc Relat Surg Off Publ Arthrosc Assoc N Am Int Arthrosc Assoc 20(8):787–794
34. Musahl V, Hoshino Y, Becker R, Karlsson J (2012) Rotatory knee laxity and the pivot shift. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 20(4):601–602
35. Hoshino Y, Araujo P, Ahldén M, Samuelsson K, Muller B, Hofbauer M, Wolf MR, Irrgang JJ, Fu FH, Musahl V (2013) Quantitative evaluation of the pivot shift by image analysis using the iPad. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 21(4):975–980
36. Daniel DM, Malcom LL, Losse G, Stone ML, Sachs R, Burks R (1985) Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am 67(5):720–726
37. Galway HR, MacIntosh DL (1980 Apr) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop (147):45–50
38. Muellner T, Bugge W, Johansen S, Holtan C, Engebretsen L (2001) Inter- and intratester comparison of the Rolimeter knee tester: effect of tester's experience and the examination technique. Knee Surg Sports Traumatol Arthrosc Off J ESSKA 9(5):302–306

Dynamic Laxity Evaluation

40

Jelle P. van der List and Andrew D. Pearle

40.1 Introduction

The function of the anterior cruciate ligament (ACL) is to prevent multiplanar instability of both anterior tibial translation (ATT) and internal tibial rotation (ITR). Slocum and Larson were the first who recognized this anteromedial instability and stated rotational laxity was too often overlooked by the inexperienced surgeon [85]. Galway and MacIntosh considered this paper as a major step forward in the biomechanical understanding and further assessed the role of rotational laxity [30, 31]. They described the lateral pivot shift phenomenon that can simulate the complaint of "giving way" of the knee in the ACL-deficient knee. They stated that the pivot shift phenomenon is a physical sign for knee examination and is pathognomonic for ACL deficiency [30, 31]. Besides the diagnostic use of the pivot shift test, this test is also correlated with functional outcomes of ACL reconstruction [7] and useful in comparing different ACL reconstruction techniques [98]. Several studies have shown that ACL reconstruction not fully restores knee kinematics in ATT [39, 57] and ITR [39, 57, 81]. The difference in kinematics between intact and ACL-reconstructed knees is thought to contribute to the failure rate (13 %) [91, 96], high percentage of patients not returning to their preinjury level of sport activity (40 %) [6, 20], and early development of osteoarthritis [46, 55].

Dynamic laxity evaluations as the pivot shift test are often used to assess knee kinematics in ACL-deficient and ACL-reconstructed knees. Dynamic laxity evaluations are considered superior over uniplanar laxity evaluations in several ways. Firstly, knee kinematics in the ACL-deficient knee are not one-dimensional but multiplanar with ATT and ITR. Static measurements as the KT-1000 arthrometer are uniplanar and do not embrace the complex, multiplanar kinematics in the ACL-deficient knees. In addition, studies have shown that uniplanar measurements are not always reliable [25, 42, 82]. Secondly, as already described by Galway and MacIntosh, the pivot shift test can simulate the "giving way" feeling of patients with ACL deficiency and therefore is a clinically relevant test [30, 31]. It has been shown that the pivot shift test and not the static laxity tests (e.g., Lachman test and KT-1000 arthrometer) is correlated with functional outcomes as satisfaction, giving way, activity limitation, and sports participation [7, 47]. Moreover, studies have shown that the postoperative pivot shift test is correlated with osteoarthritis at later follow-up [19, 43]. Thirdly, the pivot shift is known for its high specificity, especially under anesthesia because muscles do not interfere with the pivot

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DOI 10.1007/978-3-662-52742-9_40

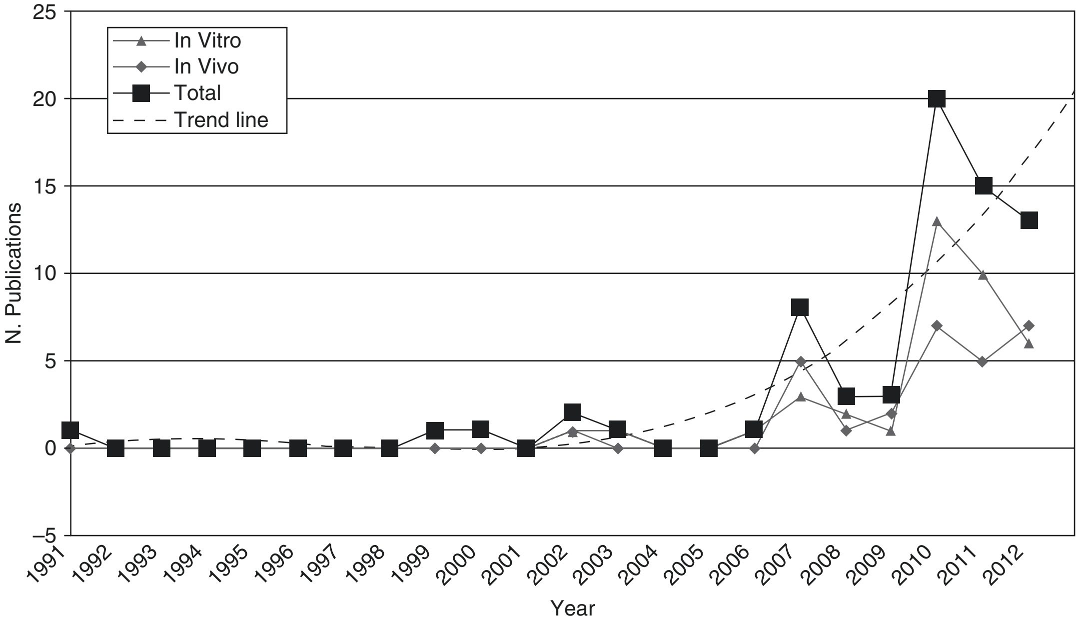

Fig. 40.1 This graph shows the number of in vitro, in vivo, and total studies that are performed on quantitative pivot shift analysis (Reprinted from Lopomo et al. [59] with kind permission of Springer Science and Business Media)

shift [50]. A meta-analysis showed a specificity of 82 % without anesthesia and 98 % with anesthesia [92], whereas specificities of the Lachman test are, respectively, 81 % and 78 % and of the anterior drawer test are, respectively, 81 % and 91 %. Taking these arguments into account, there are several arguments of using dynamic laxity evaluation over static uniplanar evaluations when assessing the function of the ACL or ACL graft.

However, there are concerns about the pivot shift test regarding the inter-rater reliability. One of the reasons is the subjective grading as assessed described by Noyes in 1991 [75] and later confirmed in other studies [72, 80]. The grading was described in a study by Jacob and colleagues [41] in which they graded the tibial subluxation as normal (grade 0), glide (grade I), clunk (grade II), or gross (grade III) although others consider grade III locked in subluxation [10, 54]. Noyes showed that not only the subjective grading but also the technique of performing a pivot shift test differed among examiners [75]. A survey among orthopedic surgeons also showed that different techniques of the pivot shift were used [51]. Because of these concerns, many studies aimed to improve the subjectivity and inter-rater reliability by quantifying the pivot shift test. Lopomo and colleagues showed that the number of in vitro and in vivo studies has significantly increased over the past two decades and the last few years the amount of in vivo studies is increasing [59] (Fig. 40.1).

In this book chapter, we discuss (1) the different methods of quantifying the pivot shift test (how to quantify the pivot shift test), (2) the different tools of measuring the pivot shift test (how to measure the pivot shift test), and (3) the different methods of performing the pivot shift test (how to perform the pivot shift test). Finally, we will discuss the future clinical application of an objective and highly reliable pivot shift.

40.2 The Pivot Shift Test

The pivot shift test as described by Galway and MacIntosh is performed starting with the knee in extension [30, 31]. With one hand, the knee is rotated internally, while with the other hand, a gentle valgus torque is applied. The knee is then moved from extension through the flexion arch, while the internal rotation is released. In the ACL-deficient knee, the tibia will translate anteriorly and rotate internally at approximately 10°–15° of flexion. When the knee is further flexed, the tibia will translate posteriorly and rotate externally toward its original position. This so-called reduction phase usually occurs between 30° and 45° of flexion [30, 31, 53]. With this method, the hip should be abducted in 45° to optimize the amount of tibial translation [8]. When the position of the tibia is visualized in the sagittal plane with knee flexion on the y-axis and ATT on the x-axis, a *P* angle is noted in ACL-deficient knees as described by Lane and colleagues [54, 78]. In the next section, we will discuss several methods of quantifying the pivot shift.

40.3 Methods of Quantifying the Pivot Shift

There are different methods to quantify the pivot shift. Some authors advocate quantifying the pivot shift by the translation of the entire tibia, whereas others only measure ATT of the lateral compartment. ITR and the acceleration of the reduction phase are also elements of the pivot shift phenomenon that could be used to quantify the pivot shift. These methods will be discussed.

40.3.1 Anterior Tibial Translation

In the years after the historical articles of Slocum and Larson and Galway and MacIntosh, several biomechanical studies quantified the anterior-posterior translation of the tibia [15, 28, 66]. These studies described the ATT in the ACL-intact and ACL-deficient knees and found significant results between both. Jakob and colleagues described the subjective grades of the pivot shift [41]. The authors assessed the ATT with anesthesia by forcing the tibia in maximal subluxation under anesthesia and estimating the anterior-posterior translation by hand. They measured both the medial and lateral compartment and found the medial compartment was a better predictor for pivot shift grading. ATT can be measured either by measuring the ATT of both compartments (so-called coupled ATT or cATT) [37] or by measuring the lateral compartment only.

Bedi and colleagues used a mechanized pivot shifter to assess the correlation between different pivot shift grades and the ATT of both the medial and lateral compartment [10]. They performed the pivot shift in 77 cadavers in where they dissected the ACL or a combination of the ACL with the medial collateral ligament, medial meniscus, lateral meniscus, or a combination of these structures. This resulted in different pivot shift grades in the cadavers. A continuous passive motion (CPM) machine was used to mechanize the pivot shift test and measured the ATT in both compartments with tracking of reference points in a three-dimensional motion path system. Contrary to the findings of Jakob and co-workers [41], they found that lateral ATT was a better predictor for a positive pivot shift (grade 0 vs. grade 1) compared with medial ATT. They found there was a threshold of 6 mm of lateral ATT for a positive pivot shift, whereas there was no significant difference between grade 0 and grade 1 in the medial compartment. Knees with a grade 0 pivot shift had an average (± SD) lateral ATT of −2.1 mm (±8.1 mm), with grade 1 an average 11.1 mm (±2.2 mm) and with grade 2 correlated with 19.6 mm (±2 mm) (Fig. 40.2). Therefore, measuring lateral ATT seems useful in the quantification of the pivot shift test.

Hoshino and colleagues assessed the lateral anterior femoral translation of the reduction phase in clinical patients, which is similar to a posterior tibial translation since these landmarks are relative to each other [35]. Under anesthesia, they performed a manual pivot shift test, and the movement of the lateral compartment was captured with skin markers and a standard digital camera and was analyzed with a two-dimensional software system. They found in 5 ACL-deficient patients with a subjective pivot shift grade 1 an anterior femoral translation in the reduction phase of 3.7 ± 2.1 mm. These authors then developed an application for a computer tablet (e.g., iPad) and performed a new study where they examined 20 patients [34]. The patients were scheduled

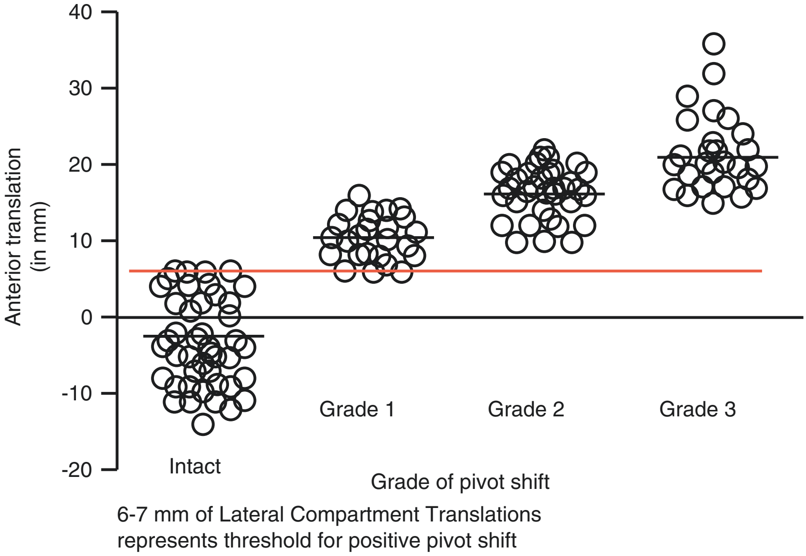

Fig. 40.2 Lateral compartment translations in mm are shown in the different pivot shift grades during a mechanized pivot shift (Reprinted from Bedi et al. [10] with kind permission of Springer Science and Business Media)

for isolated ACL reconstruction and the pivot shift was grade 1 in 10 patients and grade 2 in 10 patients. With the same method, they measured the lateral anterior femoral translation in the reduction phase and found a significant difference between grade 1 (2.7 mm ± 0.6 mm) and grade 2 (3.6 mm ± 1.2 mm). These studies showed that measuring the lateral ATT and posterior translation in the reduction phase are both reliable in quantifying the pivot shift.

40.3.2 Internal Tibial Rotation

The role of ITR in quantifying the pivot shift has also been extensively assessed [14, 21, 23, 40, 60, 62]. Bull and colleagues showed a strong correlation between the pivot shift and ITR [14]. They described that the tibia during the pivot shift test between 0° and 25° flexion showed progressive ITR, and this was suddenly reversed during the reduction phase starting at 36° (±9°) with external tibial rotation. After ACL reconstruction, this external rotation in the reduction phase was significantly reduced. Colombet and colleagues found similar results [17] when they performed manual pivot shift tests in four cadavers and measured the ITR in ACL-intact and ACL-deficient knees. They found that internal rotation was larger in the positive pivot shift (≥ grade 1) compared to the negative pivot shift (27° ± 2° vs. 20° ± 2°). Lane and colleagues found an in vivo significant correlation ($R^2 = 0.77$) between pivot shift grades and tibial rotation in the reduction phase [54]. Although some studies showed a high ICC for measuring ITR [62, 84], several authors state that there is a lack of validated devices for assessing rotatory knee laxity, and these techniques are considered complex and invasive and are therefore clinically not applicable [2, 3, 5, 21]. Diermann and colleagues performed a simulated pivot shift test at different flexion angles and compared ACL-intact, ACL-deficient, and ACL-reconstructed knees [21]. They did not find significant differences in ITR between the different knees, but they did find significant differences in ATT of the lateral compartment when comparing these knees. They suggested using lateral compartment ATT rather than internal rotation to assess the integrity of the ACL. Hoshino and colleagues also found that tibial rotation is not reliable in differentiating a negative from a positive pivot shift and recommended using lateral ATT or acceleration [36]. Moreover, some systematic reviews of rotational laxity are not convinced of clinical application of measuring internal tibial rotation and state that simple, accurate, and noninvasive devices are needed [2, 3, 5]. It seems there are differences in ITR between different pivot shift grades, but these are not easy measurable with the available devices.

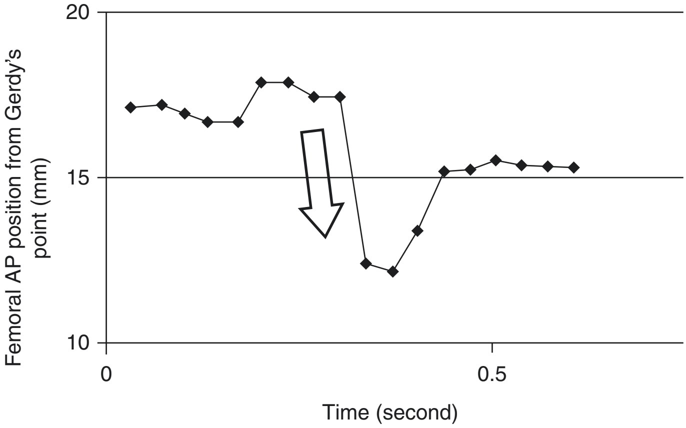

Fig. 40.3 This graph shows anterior-posterior translation (AP) of the distal femur (*y*-axis) over time (*x*-axis) during a manual pivot shift test. In the reduction phase anterior acceleration of the distal femur is seen with 5.7 mm in 0.17 s (*arrow*) (Reprinted from Hoshino et al. [35] with kind permission of Springer Science and Business Media)

40.3.3 Acceleration

More recently authors have quantified the pivot shift by measuring the acceleration of the tibia in the reduction phase (Fig. 40.3). Several studies have described the acceleration and used acceleration to differentiate between different pivot shift grades. Hoshino and colleagues assessed the acceleration of the reduction phase in 30 clinical patients under anesthesia [37]. They measured the acceleration with an electromagnetic system in a manually performed pivot shift. In the negative pivot shift, the acceleration was −795 mm^2/s, while in grade 1, 2, and 3 pivot shifts, the accelerations were, respectively, −1247 mm^2/s, −2381 mm^2/s, and −2735 mm^2/s. These accelerations were significantly different from negative pivot shift, and acceleration of tibial reduction was larger in correlation with higher clinical grading ($p<0.01$). Other authors also assessed the relationship between acceleration and pivot shift grades and reported a strong correlation between acceleration and different pivot shift grades [3, 11, 50, 51, 54, 59–61, 65]. Labbe and colleagues assessed different components of pivot shift grades (tibial translation, rotation and acceleration) in 127 in vivo pivot shifts [52]. They found that acceleration of tibial translation better distinguished the different pivot shift grades than tibial translation and tibial rotation. Ahlden and colleagues compared the relationship of acceleration and ATT with clinical pivot shift grades using electromagnetic sensors and skin sensors [1]. With both methods, the authors found a stronger correlation between acceleration and clinical pivot shift grades than ATT with clinical grades. Contrary, Lopomo and colleagues showed in a linear regression that rotational laxity before and after reconstruction is better evaluated by measuring lateral ATT compared with measuring acceleration [58]. However, there are many studies in the literature that support using both lateral ATT and acceleration in quantifying the pivot shift and different pivot shift grades. Because several studies question the use of tibial rotation in quantifying the pivot shift, development of simple devices is necessary before reliable and clinically applicable ITR measurements can be performed.

40.4 Tools to Measure the Pivot Shift

Jakob and colleagues were the first to quantify the pivot shift and measured medial and lateral ATT manually [41]. In the same study, they aimed to quantify the pivot shift by taking radiographs while forcing the tibia in a maximal subluxed position. In the years that followed, several different measurement systems were used and these different methods will be discussed.

40.4.1 Six-Degree-of-Freedom Robot

The six-degree-of-freedom robot is used in biomechanical studies. A knee is transected at the

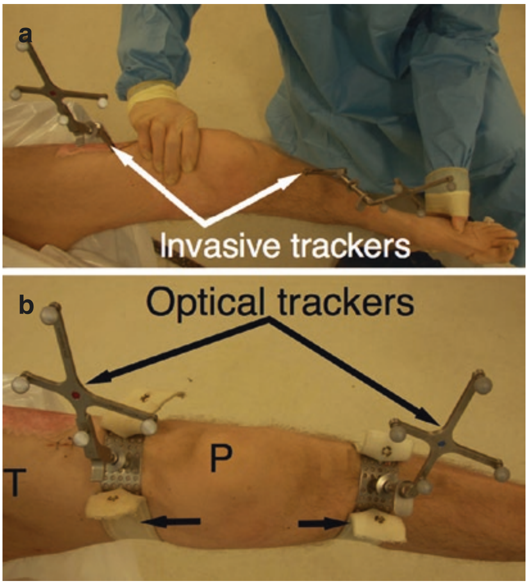

Fig. 40.4 Two photographs showing different methods of using reflective markers for navigation tracking; (**a**) (*upper*) shows a manual pivot shift with the invasive method of two pins in the distal femur and proximal tibia; (**b**) (*lower*) shows the noninvasive method of a strapping and baseplate to which the optical trackers are mounted (Reprinted from Russell et al. [83] with kind permission of Springer Science and Business Media)

proximal tibia and distal femur and the bones are mounted to the robot. The robot is a six-joint manipulator, which can learn complex multiplanar kinematics [27]. The robot can perform a combination of movements that simulate the pivot shift and register the kinematics and loads with the universal force sensor. After ACL dissection, the robot can (1) repeat the intact ACL kinematics and measure the load carried by the ACL and (2) learn the new kinematics in the ACL-deficient knee and measure the pathologic kinematics. The repeatability of this system is very high (within 0.02 mm and 0.02°) [27, 95].

40.4.2 Navigation

With this measurement technique, threaded Steinmann pins are drilled in the proximal femur and distal tibia. Reflective markers are attached to the pins and a sensor can track the position of the markers (Fig. 40.4a) [72]. With repetitive cycling of the leg, the center of rotation can be determined, and the reflective markers can measure the position of the distal femur and proximal tibia. With these positions, a three-dimensional model is created, and ATT and ITR can be measured when the knee is cycled from extension through flexion. This measurement system is accurate within 1 mm and within 1° when compared to a six-degree-of-freedom robot [18, 79]. A disadvantage of this method is the invasive technique where pins are drilled in the femur and proximal tibia. In order to use this method in the clinical setting, noninvasive methods have to be developed. A study by Russell and colleagues has used a noninvasive method by attaching the pins and reflective markers to a fabric band that is strapped around the femur (Fig. 40.4b) [83]. They showed a similar ICC for internal rotation for the noninvasive method (0.94) and invasive method (0.93). Future studies must show the clinical use of these markers in both ATT and acceleration.

40.4.3 Radiological Imaging

Some studies have used radiological imaging techniques to quantify the pivot shift. As previously discussed, Jakob and colleagues used radiography of the subluxed tibia to measure the ATT [41]. More recently, magnetic resonance imaging (MRI) is used to quantify the pivot shift [23, 32, 76, 77]. Okazaki and colleagues were one of the first to use an open MRI for the quantification of the pivot shift [76]. Patients with ACL-intact knees or ACL-deficient knees were scanned with and without manual application of anterior drawer force. In the ACL-intact knee, the lateral ATT was without stress −2 mm ± 1.5 mm and with stress 8.7 ± 8.0 mm. In the ACL-deficient knee, the lateral ATT was 8.7 mm (±8.0 mm) without stress. and with stress the lateral ATT was increased to 14.4 mm (±5.5 mm). The intra-rater reliability and inter-rater reliability for the lateral compartment were, respectively, 0.98 and 0.91. Although the MRI showed reliable lateral ATT increase in the ACL-deficient knee, it is expensive and not applicable in the clinical setting. Furthermore, it is difficult to use this for dynamic laxity evaluation.

40.4.4 Radiostereometric Analysis

Radiostereometric analysis (RSA) is an imaging technique that can be used to measure knee laxity in a dynamic setting [26]. With this technique, tantalum beads are implanted in the tibia and femur, and with biplanar radiographs, the exact amount of ATT can be measured while a patient is walking or running. The measurements are accurate within 10–250 μm and 0.03–0.06°, and an important advantage of this method is the possibility to measure the ATT during walking or running [26, 89]. To overcome the invasive implanting of tantalum beads, Tashman and colleagues developed a CT-imaging technique [88]. Although RSA can be used noninvasively, these measurements are considered expensive and labor-intensive, and radiation is used [2]. Some authors consider this method as the gold standard [2], but it is not widely applicable in the clinical setting.

40.4.5 Electromagnetic Device

Hoshino and colleagues used an electromagnetic device in clinical patients to quantify the pivot shift test [37]. This device consists of a transmitter that produces an electromagnetic field and three receivers. The receiver is attached to a strap, and two receivers are placed 10 cm above the patella on the proximal femur and approximately 10 cm below the patella. A third receiver was used to digitize several anatomical landmarks (Fig. 40.5). The electromagnetic system has gained increased popularity over the last decade [1, 4, 22, 56, 59, 90] and is shown to have good accuracy for both positioning (0.76 mm) and orientation (0.158°) [74].

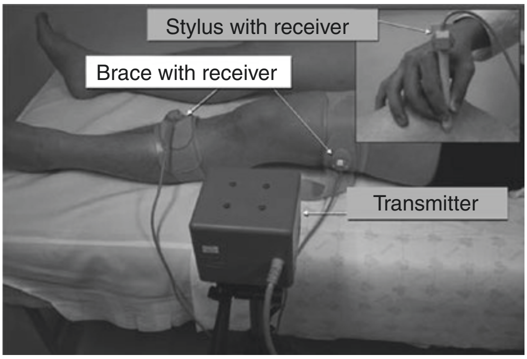

Fig. 40.5 This photograph shows the electromagnetic device that is used to quantify the pivot shift test. A transmitter sends signals to two braces with receivers that are strapped around the distal femur and proximal tibia. A third stylus with receiver (*upper right*) is used to acquire different anatomical landmarks (Reprinted from Hoshino et al. [37] with kind permission of American Journal of Sports Medicine)

40.4.6 Skin Markers

Recently, a measuring system with digital cameras and skin markers has been introduced [34, 35]. With this technique, three skin markers are attached to (1) Gerdy's tubercle, (2) the fibular head, and (3) the lateral epicondyle. The digital camera records the movement of the skin markers and thus the movement of the lateral femur and tibia (Fig. 40.6). The authors showed in these two studies that this measuring system is able to measure ATT and tibial acceleration in the reduction phase. Advantages of this system are the low threshold for using skin markers and digital cameras in the clinical setting, and this could be of value for future clinical application. However, some problems have to be overcome. First of all, even when the skin markers are properly attached, they are less accurate because they allow motion artifacts between skin and bone [3, 13, 64]. Secondly, although this measuring method ensures objective measurement of the pivot shift test, the manual performing of the pivot shift does not ensure objective results compared to a mechanized pivot shift test [72]. The different performing techniques of the pivot shift will be discussed next.

40.4.7 Inertial Sensor

The use of inertial sensors for the quantification of the pivot shift test [61] will be treated deep in the dedicated chapter.

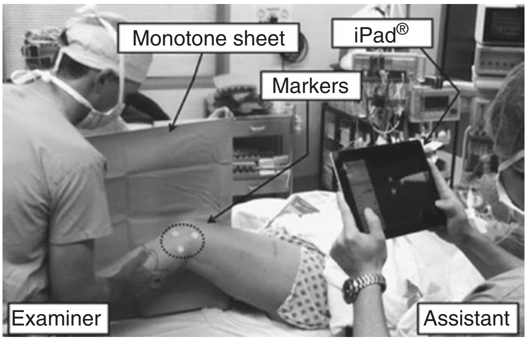

Fig. 40.6 The setup of quantifying the pivot shift with skin markers is shown in the clinical setting. The three skin markers are placed at Gerdy's tubercle, the fibular head, and the lateral epicondyle. An iPad is used to measure the movement of the skin markers during a manual pivot shift, while a sheet is placed at the background to minimize interference (Reprinted from Hoshino et al. [34] with kind permission of Springer Science and Business Media)

40.5 Methods of Performing the Pivot Shift

For the purpose of quantification of the pivot shift, three general methods are seen in the literature. In the 1990s, several studies used the biomechanical technique of the simulated pivot shift in order to quantify the pivot shift [58, 59, 87]. Other studies used the manual pivot shift, whereas the senior author (AP) used the mechanized pivot shifter to quantify the pivot shift. These three different methods of performing the pivot shift will be discussed.

40.5.1 Simulated Pivot Shift Test

Many biomechanical studies used the six-degree-of-freedom robot with universal force sensor to quantify the pivot shift with a simulated pivot shift test [22, 29, 44, 45, 48, 49, 59, 67, 97, 99]. Matsumoto and colleagues assessed the role of several structures in the knee on the pivot shift [67], and they found that solitary ACL injury, solitary lateral structure injury, and combined ACL and lateral structure injury could cause a positive pivot shift. With this study, they objectively confirmed the results of other studies that used the manual pivot shift [24, 38, 63]. Kanamori and colleagues further quantified the ATT in the ACL-intact and ACL-deficient knee with the simulated pivot shift [44]. They reported that different ATT between ACL-intact and ACL-deficient knees was seen between 0° and 30° of flexion. In a follow-up study, they assessed the role of internal torque and valgus torque on the ATT of the pivot shift [45]. They found that a 10 Nm valgus torque gave the largest difference in ATT between the ACL-intact and ACL-deficient knee, which is confirmed by others [29]. The largest difference in ATT between the ACL-intact and ACL-deficient knee was seen with a 1.6 Nm rotational torque and a 10 Nm valgus torque. The authors therefore suggested that optimal performance of the pivot shift requires a moderate amount of valgus force with only a small internal rotation torque. Engebretsen and colleagues performed a simulated pivot shift test and compared the applying of different torques and forces. The authors confirmed that coupled internal rotation and valgus torques best recreated the lateral ATT that occurs in the simulated pivot shift test [22].

40.5.2 Manual Pivot Shift Test

Many studies used the manual pivot shift to quantify the pivot shift. One of the great advantages of the manual pivot shift is the fact that no equipment or additional personal is necessary and results are immediately obtained [12]. However, one major disadvantage is the difference in technique among examiners. In a survey among 33 orthopedic surgeons, several differences in technique and reporting outcomes were detected [51]. More specific, 60 % of the surgeons performed flexion from extended position, whereas 40 % performed extension from flexed position, and 70 % applied internal rotation during the pivot shift test, while 30 % applied external rotation. In addition, the authors compared the quantified pivot shift between five examiners with an electromagnetic device. They found no differences in ATT and acceleration between the examiners but did find differences in ITR and when the

Fig. 40.7 A human cadaver is placed in the mechanized pivot shifter, and the examiner pushes the handle of the foot driver component while pulling the handle of the base plate. This causes flexion of the knee and will induce the pivot shift phenomenon. Please note that the foot is in external rotation in this photograph (Reprinted from Citak et al. [16] with kind permission of Springer Science and Business Media)

pivot shift was applied in the contralateral knee [51]. Because of different surgeon preferences in the pivot shift technique, a standardized pivot shift test is suggested [33, 71]. In the first step, the leg is in extension with slight hip abduction and the leg is internally rotated. In the second step, gentle valgus stress is applied and the leg is brought into flexion. The internal rotation is maintained until 20° of flexion and is then released when the knee is further flexed. Between 20° and 40° of flexion, the reduction phase occurs, and posterior translation of the tibia along with external rotation can be measured. Hoshino and colleagues [33] compared the inter-rater variability among 12 orthopedic surgeons and found a smaller variability in the standardized technique compared to their preferred technique. However, it remains difficult to quantify the pivot shift with a manual examination since educational differences and preferences in technique exist among orthopedic surgeons.

40.5.3 Mechanized Pivot Shift

The senior author (AP) and colleagues used a mechanized pivot shifter in order to quantify the pivot shift test in human cadavers. A whole hip-to-toe cadaver is mounted to a setup, and a CPM machine is secured to the table. The foot is placed in a holder and fixed in an internal rotation moment at the knee. A valgus moment is applied with a three-degree-of-freedom arm, and the leg is moved from extension through the flexion arch (Fig. 40.7). The mechanized pivot shift test was compared to the manual pivot shift test and was found to be more accurate in measuring ATT than the manual performed pivot shift test (0.92 vs. 0.76, respectively) [72]. A second-generation mechanized tester was developed which was more accurate than the first generation (0.99 vs. 0.92, respectively) [16]. With this mechanized pivot shift test, the examiners quantified the role of the primary and secondary stabilizers on in ATT and ITR [10, 68, 70, 86, 94]. They were also able to assess the influence of different tunnel positions on knee stability [9, 93] and compared different reconstruction techniques in knee stability with the meniscus [73] and without the meniscus [69] in situ.

The mechanized pivot shift is shown to have high ICC and is able to distinguish different pivot shift grades as earlier discussed. However, the setup of this method is invasive since Steinmann pins are drilled in the distal femur and proximal tibia. Therefore, this method is not applicable in the clinical setting. As previously discussed, some studies have examined the application of noninvasive reflective markers on Steinmann pins [83] and found a high ICC for internal rotation. Further research is needed to show reliability in ATT and acceleration. Furthermore, it would be of value to further develop the mechanized pivot shifter to a device that can be easily used in the clinical setting.

40.6 Clinical Application

Several studies have reported objective measuring of the ATT, ITR, or tibial acceleration of the pivot shift, and some of these methods have potential to be of clinical value. Measuring lateral ATT or acceleration is currently the most reliable and cost-efficient in quantifying the pivot shift test [5]. The use of skin markers seems promising since the markers are easy to use, have low costs, and can reliably measure the lateral ATT [35]. Other measurement methods as electromagnetic devices, inertial sensors, and noninvasive reflective markers also have clinical potential [37, 61, 83]. However, a problem with noninvasive methods remains the skin-bone movement and marker-skin movement, and the test should be corrected for these movements [3, 13, 64]. The method of performing the pivot shift test can be manual with a standardized method or with a mechanized pivot shift test. The mechanized pivot shift test is more objective than the manual pivot shift since there are still differences in performing the pivot shift test. However, an easy, smaller, and low-cost mechanizer needs to be developed to enable clinical use as is seen with the KT-1000. Over the last years, several studies have assessed the role of the quantified pivot shift test in the clinical setting. Hopefully, this will lead to the ultimate goal of a worldwide available and affordable device that can be used to diagnose and evaluate the ACL in the clinical setting.

Conclusion

The KT-1000 arthrometer is commonly used as clinical evaluation to standardize and quantify the anterior tibial rotation. Dynamic laxity evaluations as the pivot shift test are superior over static laxity evaluations as the KT-1000 with regard to the multiplanar kinematics of the knee, the simulation of the "giving way" feeling of the patient, and the high specificity of the test. However, the pivot shift is subjectivity and high inter-rater variability must be overcome before the pivot shift test can be objectively used in the clinical setting. Several studies have tried to objectify and standardize the pivot shift test in lateral ATT, ITR, or acceleration of the reduction phase. With all three methods of quantification, reliable and accurate results were found although lateral ATT and acceleration seem easier applicable in the clinical setting. In vivo measurements as navigation systems with three-dimensional models, radiostereometric analysis, electromagnetic devices, inertial sensors, and skin markers are developed to measure the ATT, ITR, or acceleration and are proven to have high reliability. Especially electromagnetic devices, inertial sensors, and skin markers are easily applicable in the clinical setting.

It is also important to have a standardized method of performing the pivot shift test in the clinical setting. Some studies have shown good results with a mechanized pivot shift test, although this device should be further developed for clinical use. Until a useful device is developed, the standardized method of the manual pivot shift test should be used. Many studies have contributed to a pivot shift test that is more objective and reliable. These studies have contributed toward the ultimate goal of using an objective and accurate dynamic laxity evaluation in the clinical setting.

References

1. Ahlden M, Araujo P, Hoshino Y, Samuelsson K, Middleton KK, Nagamune K, Karlsson J, Musahl V (2012) Clinical grading of the pivot shift test correlates best with tibial acceleration. Knee Surg Sports Traumatol Arthrosc 20(4):708–712
2. Ahlden M, Hoshino Y, Samuelsson K, Araujo P, Musahl V, Karlsson J (2012) Dynamic knee laxity

measurement devices. Knee Surg Sports Traumatol Arthrosc 20(4):621–632

3. Ahlden M, Samuelsson K, Fu FH, Musahl V, Karlsson J (2013) Rotatory knee laxity. Clin Sports Med 32(1):37–46
4. Anderson CJ, Westerhaus BD, Pietrini SD, Ziegler CG, Wijdicks CA, Johansen S, Engebretsen L, Laprade RF (2010) Kinematic impact of anteromedial and posterolateral bundle graft fixation angles on double-bundle anterior cruciate ligament reconstructions. Am J Sports Med 38(8):1575–1583
5. Araujo PH, Kfuri Junior M, Ohashi B, Hoshino Y, Zaffagnini S, Samuelsson K, Karlsson J, Fu F, Musahl V (2014) Individualized ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 22(9):1966–1975
6. Ardern CL, Webster KE, Taylor NF, Feller JA (2011) Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med 45(7):596–606
7. Ayeni OR, Chahal M, Tran MN, Sprague S (2012) Pivot shift as an outcome measure for ACL reconstruction: a systematic review. Knee Surg Sports Traumatol Arthrosc 20(4):767–777
8. Bach BR Jr, Warren RF, Wickiewicz TL (1988) The pivot shift phenomenon: results and description of a modified clinical test for anterior cruciate ligament insufficiency. Am J Sports Med 16(6):571–576
9. Bedi A, Maak T, Musahl V, Citak M, O'Loughlin PF, Choi D, Pearle AD (2011) Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important? Am J Sports Med 39(2): 366–373
10. Bedi A, Musahl V, Lane C, Citak M, Warren RF, Pearle AD (2010) Lateral compartment translation predicts the grade of pivot shift: a cadaveric and clinical analysis. Knee Surg Sports Traumatol Arthrosc 18(9):1269–1276
11. Bignozzi S, Zaffagnini S, Lopomo N, Fu FH, Irrgang JJ, Marcacci M (2010) Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18(1):37–42
12. Branch TP, Mayr HO, Browne JE, Campbell JC, Stoehr A, Jacobs CA (2010) Instrumented examination of anterior cruciate ligament injuries: minimizing flaws of the manual clinical examination. Arthroscopy 26(7):997–1004
13. Bull AM, Berkshire FH, Amis AA (1998) Accuracy of an electromagnetic measurement device and application to the measurement and description of knee joint motion. Proc Inst Mech Eng H 212(5):347–355
14. Bull AM, Earnshaw PH, Smith A, Katchburian MV, Hassan AN, Amis AA (2002) Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br 84(7):1075–1081
15. Butler DL, Noyes FR, Grood ES (1980) Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. J Bone Joint Surg Am 62(2):259–270
16. Citak M, Suero EM, Rozell JC, Bosscher MR, Kuestermeyer J, Pearle AD (2011) A mechanized and standardized pivot shifter: technical description and first evaluation. Knee Surg Sports Traumatol Arthrosc 19(5):707–711
17. Colombet P, Jenny JY, Menetrey J, Plaweski S, Zaffagnini S (2012) Current concept in rotational laxity control and evaluation in ACL reconstruction. Orthop Traumatol Surg Res 98(8 Suppl):S201–S210
18. Colombet P, Robinson J, Christel P, Franceschi JP, Djian P (2007) Using navigation to measure rotation kinematics during ACL reconstruction. Clin Orthop Relat Res 454:59–65
19. Conteduca F, Ferretti A, Mariani PP, Puddu G, Perugia L (1991) Chondromalacia and chronic anterior instabilities of the knee. Am J Sports Med 19(2):119–123
20. Denti M, Lo Vetere D, Bait C, Schonhuber H, Melegati G, Volpi P (2008) Revision anterior cruciate ligament reconstruction: causes of failure, surgical technique, and clinical results. Am J Sports Med 36(10): 1896–1902
21. Diermann N, Schumacher T, Schanz S, Raschke MJ, Petersen W, Zantop T (2009) Rotational instability of the knee: internal tibial rotation under a simulated pivot shift test. Arch Orthop Trauma Surg 129(3):353–358
22. Engebretsen L, Wijdicks CA, Anderson CJ, Westerhaus B, LaPrade RF (2012) Evaluation of a simulated pivot shift test: a biomechanical study. Knee Surg Sports Traumatol Arthrosc 20(4): 698–702
23. Espregueira-Mendes J, Pereira H, Sevivas N, Passos C, Vasconcelos JC, Monteiro A, Oliveira JM, Reis RL (2012) Assessment of rotatory laxity in anterior cruciate ligament-deficient knees using magnetic resonance imaging with Porto-knee testing device. Knee Surg Sports Traumatol Arthrosc 20(4):671–678
24. Fetto JF, Marshall JL (1979) Injury to the anterior cruciate ligament producing the pivot-shift sign. J Bone Joint Surg Am 61(5):710–714
25. Fleming BC, Brattbakk B, Peura GD, Badger GJ, Beynnon BD (2002) Measurement of anterior-posterior knee laxity: a comparison of three techniques. J Orthop Res 20(3):421–426
26. Fleming BC, Peura GD, Abate JA, Beynnon BD (2001) Accuracy and repeatability of Roentgen stereophotogrammetric analysis (RSA) for measuring knee laxity in longitudinal studies. J Biomech 34(10):1355–1359
27. Fujie H, Mabuchi K, Woo SL-Y, Livesay GA, Arai S, Tsukamoto Y (1993) The use of robotics technology to study human joint kinematics: a new methodology. J Biomech Eng 115(3):211–217
28. Fukubayashi T, Torzilli PA, Sherman MF, Warren RF (1982) An in vitro biomechanical evaluation of anterior-posterior motion of the knee. Tibial displacement, rotation, and torque. J Bone Joint Surg Am 64(2):258–264

29. Fukuda Y, Woo SL, Loh JC, Tsuda E, Tang P, McMahon PJ, Debski RE (2003) A quantitative analysis of valgus torque on the ACL: a human cadaveric study. J Orthop Res 21(6):1107–1112
30. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
31. Galway R, Beaupre A, MacIntosh D (1972) Pivot shift: a clinical sign of symptomatic anterior cruciate insufficiency. J Bone Joint Surg Br 54:763–764
32. Haughom BD, Souza R, Schairer WW, Li X, Ma CB (2012) Evaluating rotational kinematics of the knee in ACL-ruptured and healthy patients using 3.0 Tesla magnetic resonance imaging. Knee Surg Sports Traumatol Arthrosc 20(4):663–670
33. Hoshino Y, Araujo P, Ahlden M, Moore CG, Kuroda R, Zaffagnini S, Karlsson J, Fu FH, Musahl V (2012) Standardized pivot shift test improves measurement accuracy. Knee Surg Sports Traumatol Arthrosc 20(4):732–736
34. Hoshino Y, Araujo P, Ahlden M, Samuelsson K, Muller B, Hofbauer M, Wolf MR, Irrgang JJ, Fu FH, Musahl V (2013) Quantitative evaluation of the pivot shift by image analysis using the iPad. Knee Surg Sports Traumatol Arthrosc 21(4):975–980
35. Hoshino Y, Araujo P, Irrgang JJ, Fu FH, Musahl V (2012) An image analysis method to quantify the lateral pivot shift test. Knee Surg Sports Traumatol Arthrosc 20(4):703–707
36. Hoshino Y, Kuroda R, Nagamune K, Araki D, Kubo S, Yamaguchi M, Kurosaka M (2012) Optimal measurement of clinical rotational test for evaluating anterior cruciate ligament insufficiency. Knee Surg Sports Traumatol Arthrosc 20(7):1323–1330
37. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 35(7): 1098–1104
38. Hughston JC, Andrews JR, Cross MJ, Moschi A (1976) Classification of knee ligament instabilities. Part II The lateral compartment. J Bone Joint Surg Am 58(2):173–179
39. Imhauser C, Mauro C, Choi D, Rosenberg E, Mathew S, Nguyen J, Ma Y, Wickiewicz T (2013) Abnormal tibiofemoral contact stress and its association with altered kinematics after center-center anterior cruciate ligament reconstruction: an in vitro study. Am J Sports Med 41(4):815–825
40. Jakob RP, Hassler H, Staeubli HU (1981) 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 191:1–32
41. Jakob RP, Staubli HU, Deland JT (1987) Grading the pivot shift. Objective tests with implications for treatment. J Bone Joint Surg Br 69(2):294–299
42. Jardin C, Chantelot C, Migaud H, Gougeon F, Debroucker MJ, Duquennoy A (1999) Reliability of the KT-1000 arthrometer in measuring anterior laxity of the knee: comparative analysis with Telos of 48 reconstructions of the anterior cruciate ligament and intra- and interobserver reproducibility. Rev Chir Orthop Reparatrice Appar Mot 85(7):698–707
43. Jonsson H, Riklund-Ahlstrom K, Lind J (2004) Positive pivot shift after ACL reconstruction predicts later osteoarthrosis: 63 patients followed 5–9 years after surgery. Acta Orthop Scand 75(5):594–599
44. Kanamori A, Woo SL, Ma CB, Zeminski J, Rudy TW, Li G, Livesay GA (2000) The forces in the anterior cruciate ligament and knee kinematics during a simulated pivot shift test: a human cadaveric study using robotic technology. Arthroscopy 16(6):633–639
45. Kanamori A, Zeminski J, Rudy TW, Li G, Fu FH, Woo SL (2002) The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy 18(4):394–398
46. Kessler MA, Behrend H, Henz S, Stutz G, Rukavina A, Kuster MS (2008) Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 16(5):442–448
47. Kocher MS, Steadman JR, Briggs KK, Sterett WI, Hawkins RJ (2004) Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med 32(3): 629–634
48. Kondo E, Merican AM, Yasuda K, Amis AA (2010) Biomechanical comparisons of knee stability after anterior cruciate ligament reconstruction between 2 clinically available transtibial procedures: anatomic double bundle versus single bundle. Am J Sports Med 38(7):1349–1358
49. Kondo E, Merican AM, Yasuda K, Amis AA (2011) Biomechanical comparison of anatomic double-bundle, anatomic single-bundle, and nonanatomic single-bundle anterior cruciate ligament reconstructions. Am J Sports Med 39(2):279–288
50. Kuroda R, Hoshino Y, Araki D, Nishizawa Y, Nagamune K, Matsumoto T, Kubo S, Matsushita T, Kurosaka M (2012) Quantitative measurement of the pivot shift, reliability, and clinical applications. Knee Surg Sports Traumatol Arthrosc 20(4):686–691
51. Kuroda R, Hoshino Y, Kubo S, Araki D, Oka S, Nagamune K, Kurosaka M (2012) Similarities and differences of diagnostic manual tests for anterior cruciate ligament insufficiency: a global survey and kinematics assessment. Am J Sports Med 40(1):91–99
52. Labbe DR, de Guise JA, Mezghani N, Godbout V, Grimard G, Baillargeon D, Lavigne P, Fernandes J, Ranger P, Hagemeister N (2010) Feature selection using a principal component analysis of the kinematics of the pivot shift phenomenon. J Biomech 43(16):3080–3084

53. Lane CG, Warren R, Pearle AD (2008) The pivot shift. J Am Acad Orthop Surg 16(12):679–688
54. Lane CG, Warren RF, Stanford FC, Kendoff D, Pearle AD (2008) In vivo analysis of the pivot shift phenomenon during computer navigated ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 16(5):487–492
55. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ (2011) Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med 39(12):2595–2603. doi:10.1177/0363546511424720
56. Lie DT, Bull AM, Amis AA (2007) Persistence of the mini pivot shift after anatomically placed anterior cruciate ligament reconstruction. Clin Orthop Relat Res 457:203–209
57. Logan MC, Williams A, Lavelle J, Gedroyc W, Freeman M (2004) Tibiofemoral kinematics following successful anterior cruciate ligament reconstruction using dynamic multiple resonance imaging. Am J Sports Med 32(4):984–992
58. Lopomo N, Signorelli C, Bonanzinga T, Marcheggiani Muccioli GM, Neri MP, Visani A, Marcacci M, Zaffagnini S (2014) Can rotatory knee laxity be predicted in isolated anterior cruciate ligament surgery? Int Orthop 38(6):1167–1172
59. Lopomo N, Zaffagnini S, Amis AA (2013) Quantifying the pivot shift test: a systematic review. Knee Surg Sports Traumatol Arthrosc 21(4):767–783
60. Lopomo N, Zaffagnini S, Bignozzi S, Visani A, Marcacci M (2010) Pivot-shift test: analysis and quantification of knee laxity parameters using a navigation system. J Orthop Res 28(2):164–169
61. Lopomo N, Zaffagnini S, Signorelli C, Bignozzi S, Giordano G, Marcheggiani Muccioli GM, Visani A (2012) An original clinical methodology for non-invasive assessment of pivot-shift test. Comput Methods Biomech Biomed Engin 15(12):1323–1328
62. Lorbach O, Wilmes P, Theisen D, Brockmeyer M, Maas S, Kohn D, Seil R (2009) Reliability testing of a new device to measure tibial rotation. Knee Surg Sports Traumatol Arthrosc 17(8):920–926
63. Losee RE (1983) Concepts of the pivot shift. Clin Orthop Relat Res 172:45–51
64. Lucchetti L, Cappozzo A, Cappello A, Della Croce U (1998) Skin movement artefact assessment and compensation in the estimation of knee-joint kinematics. J Biomech 31(11):977–984
65. Maeyama A, Hoshino Y, Debandi A, Kato Y, Saeki K, Asai S, Goto B, Smolinski P, Fu FH (2011) Evaluation of rotational instability in the anterior cruciate ligament deficient knee using triaxial accelerometer: a biomechanical model in porcine knees. Knee Surg Sports Traumatol Arthrosc 19(8):1233–1238
66. Markolf KL, Mensch JS, Amstutz HC (1976) Stiffness and laxity of the knee – the contributions of the supporting structures. A quantitative in vitro study. J Bone Joint Surg Am 58(5):583–594
67. Matsumoto H (1990) Mechanism of the pivot shift. J Bone Joint Surg Br 72(5):816–821
68. Musahl V, Ayeni OR, Citak M, Irrgang JJ, Pearle AD, Wickiewicz TL (2010) The influence of bony morphology on the magnitude of the pivot shift. Knee Surg Sports Traumatol Arthrosc 18(9):1232–1238
69. Musahl V, Bedi A, Citak M, O'Loughlin P, Choi D, Pearle AD (2011) Effect of single-bundle and double-bundle anterior cruciate ligament reconstructions on pivot-shift kinematics in anterior cruciate ligament- and meniscus-deficient knees. Am J Sports Med 39(2):289–295
70. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD (2010) The effect of medial versus lateral meniscectomy on the stability of the anterior cruciate ligament-deficient knee. Am J Sports Med 38(8):1591–1597
71. Musahl V, Hoshino Y, Ahlden M, Araujo P, Irrgang JJ, Zaffagnini S, Karlsson J, Fu FH (2012) The pivot shift: a global user guide. Knee Surg Sports Traumatol Arthrosc 20(4):724–731
72. Musahl V, Voos J, O'Loughlin PF, Stueber V, Kendoff D, Pearle AD (2010) Mechanized pivot shift test achieves greater accuracy than manual pivot shift test. Knee Surg Sports Traumatol Arthrosc 18(9):1208–1213
73. Musahl V, Voos JE, O'Loughlin PF, Choi D, Stueber V, Kendoff D, Pearle AD (2010) Comparing stability of different single- and double-bundle anterior cruciate ligament reconstruction techniques: a cadaveric study using navigation. Arthroscopy 26(9 Suppl):S41–S48
74. Nafis C, Jensen V, Beauregard L, Anderson P (2006) Method for estimating dynamic EM tracking accuracy of surgical navigation tools. In: Medical imaging. International Society for Optics and Photonics, San Diego, CA, pp 61410K-61410K-61416
75. Noyes FR, Grood ES, Cummings JF, Wroble RR (1991) An analysis of the pivot shift phenomenon. The knee motions and subluxations induced by different examiners. Am J Sports Med 19(2):148–155
76. Okazaki K, Miura H, Matsuda S, Yasunaga T, Nakashima H, Konishi K, Iwamoto Y, Hashizume M (2007) Assessment of anterolateral rotatory instability in the anterior cruciate ligament-deficient knee using an open magnetic resonance imaging system. Am J Sports Med 35(7):1091–1097
77. Okazaki K, Tashiro Y, Izawa T, Matsuda S, Iwamoto Y (2012) Rotatory laxity evaluation of the knee using modified Slocum's test in open magnetic resonance imaging. Knee Surg Sports Traumatol Arthrosc 20(4):679–685
78. Pearle AD, Kendoff D, Musahl V, Warren RF (2009) The pivot-shift phenomenon during computer-assisted anterior cruciate ligament reconstruction. J Bone Joint Surg Am 91(Suppl 1):115–118
79. Pearle AD, Solomon DJ, Wanich T, Moreau-Gaudry A, Granchi CC, Wickiewicz TL, Warren RF (2007) Reliability of navigated knee stability examination: a cadaveric evaluation. Am J Sports Med 35(8):1315–1320

80. Peeler J, Leiter J, MacDonald P (2010) Accuracy and reliability of anterior cruciate ligament clinical examination in a multidisciplinary sports medicine setting. Clin J Sport Med 20(2):80–85
81. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD (2005) Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. Arthroscopy 21(11):1323–1329
82. Robert H, Nouveau S, Gageot S, Gagniere B (2009) A new knee arthrometer, the GNRB: experience in ACL complete and partial tears. Orthop Traumatol Surg Res 95(3):171–176
83. Russell DF, Deakin AH, Fogg QA, Picard F (2014) Repeatability and accuracy of a non-invasive method of measuring internal and external rotation of the tibia. Knee Surg Sports Traumatol Arthrosc 22(8): 1771–1777
84. Shultz SJ, Shimokochi Y, Nguyen AD, Schmitz RJ, Beynnon BD, Perrin DH (2007) Measurement of varus-valgus and internal-external rotational knee laxities in vivo – part I: assessment of measurement reliability and bilateral asymmetry. J Orthop Res 25(8):981–988
85. Slocum DB, Larson RL (1968) Rotatory instability of the knee. Its pathogenesis and a clinical test to demonstrate its presence. J Bone Joint Surg Am 50(2): 211–225
86. Suero EM, Njoku IU, Voigt MR, Lin J, Koenig D, Pearle AD (2013) The role of the iliotibial band during the pivot shift test. Knee Surg Sports Traumatol Arthrosc 21(9):2096–2100
87. Tanaka M, Vyas D, Moloney G, Bedi A, Pearle AD, Musahl V (2012) What does it take to have a high-grade pivot shift? Knee Surg Sports Traumatol Arthrosc 20(4):737–742
88. Tashman S (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983
89. Tashman S, Anderst W (2003) In-vivo measurement of dynamic joint motion using high speed biplane radiography and CT: application to canine ACL deficiency. J Biomech Eng 125(2):238–245
90. Tsai AG, Wijdicks CA, Walsh MP, Laprade RF (2010) Comparative kinematic evaluation of all-inside single-bundle and double-bundle anterior cruciate ligament reconstruction: a biomechanical study. Am J Sports Med 38(2):263–272
91. van Eck CF, Schkrohowsky JG, Working ZM, Irrgang JJ, Fu FH (2012) Prospective analysis of failure rate and predictors of failure after anatomic anterior cruciate ligament reconstruction with allograft. Am J Sports Med 40(4):800–807. doi:10.1177/0363546511432545
92. van Eck CF, van den Bekerom MP, Fu FH, Poolman RW, Kerkhoffs GM (2013) Methods to diagnose acute anterior cruciate ligament rupture: a meta-analysis of physical examinations with and without anaesthesia. Knee Surg Sports Traumatol Arthrosc 21(8): 1895–1903
93. Voos JE, Musahl V, Maak TG, Wickiewicz TL, Pearle AD (2010) Comparison of tunnel positions in single-bundle anterior cruciate ligament reconstructions using computer navigation. Knee Surg Sports Traumatol Arthrosc 18(9):1282–1289
94. Voos JE, Suero EM, Citak M, Petrigliano FP, Bosscher MR, Citak M, Wickiewicz TL, Pearle AD (2012) Effect of tibial slope on the stability of the anterior cruciate ligament-deficient knee. Knee Surg Sports Traumatol Arthrosc 20(8):1626–1631
95. Woo SLY, Fox RJ, Sakane M, Livesay GA, Rudy TW, Fu FH (1998) Biomechanics of the ACL: measurements of in situ force in the ACL and knee kinematics. Knee 5(4):267–288
96. Wright RW, Gill CS, Chen L, Brophy RH, Matava MJ, Smith MV, Mall NA (2012) Outcome of revision anterior cruciate ligament reconstruction: a systematic review. J Bone Joint Surg Am 94(6):531–536. doi:10.2106/JBJS.K.00733
97. Yamamoto Y, Ishibashi Y, Tsuda E, Tsukada H, Maeda S, Toh S (2010) Comparison between clinical grading and navigation data of knee laxity in ACL-deficient knees. Sports Med Arthrosc Rehabil Ther Technol 2:27
98. Zaffagnini S, Marcheggiani Muccioli GM, Lopomo N, Signorelli C, Bonanzinga T, Musiani C, Vassilis P, Nitri M, Marcacci M (2012) Can the pivot-shift be eliminated by anatomic double-bundle anterior cruciate ligament reconstruction? Knee Surg Sports Traumatol Arthrosc 20(4):743–751
99. Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W (2007) The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. Am J Sports Med 35(2):223–227

The Role of Navigation Systems in ACL Reconstruction

41

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Fact Boxes

- *Navigation in ACL surgery is an important tool improving tunnel placement and laxity evaluation of injured knees.*
- *The navigation system can improve clinical outcomes and decrease the failure rate of ACL reconstruction.*

41.1 History of Computer-Assisted Orthopedic Surgery for ACL Reconstruction

Computer-assisted orthopedic surgery (CAOS) began in the 1990s. Its first application was used in spinal surgery to minimize the risk of damaging neurovascular structures when pedicle screws were inserted into the vertebra [40]. Development of CAOS then expanded into hip and knee arthroplasty in order to improve the positioning of the implant [1]. CAOS, particularly in conjunction with a navigation system, has also been applied to anterior cruciate ligament (ACL) reconstruction since the mid-1990s [8]. Failure of ACL reconstruction was often due to technical errors, such as inappropriate tunnel position of the graft. Navigation system was introduced in ACL reconstruction to reduce such errors and was focused on improving the accuracy and reproducibility of the tunnel placement. Since the 2000s, navigation systems have been used increasingly as a quantitative measurement tool to assess ACL graft obliquity or for visualization of the pivot shift (PS) phenomenon [21]. Not only can the surgeon confirm the virtual tunnel position, but they can also decipher important information such as the risk of graft impingement, graft isometricity, and accurate assessment of laxity patterns intraoperatively on the navigation display. Thus, navigation systems have the potential to improve outcomes after ACL reconstruction by reducing variability in tunnel positions and improving their accuracy. To that end, a number of investigators have reported their experience with navigation-assisted ACL reconstruction; we discuss some of their findings in this chapter.

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Table 41.1 Randomized control trials of ACL reconstruction with or without navigation system

Author	Publication year	Number of patients		Average age (range)	Male/female	Navigation system	Average follow-up (months)
		Navigation group	Conventional group				
Plaweski et al.	2006	30	30	30 (16–50)	40:20	Image-free (surgetics)	24
Mauch et al.	2007	29	24	34 (18–49)	17:36	Image-free (OrthoPilot)	NS
Chouteau et al.	2008	37	36	27 (14–53)	46:27	Image-based (original system)	26.4
Hart et al.	2008	40	40	29.4 (16–39)	64:16	Image-free (OrthoPilot)	28
Meuffels et al.	2012	49	51	NS (>18)	24:76	Image-based (VectorVision)	NS

NS not stated

41.2 Navigation Types for ACL Reconstruction

There are two types of navigation systems for ACL reconstruction: image-based (e.g., VectorVision ACL 1.0, Brainlab, Heimstetten, Germany; Stealth Station iON, Medtronic, Louisville, USA) and image-free (e.g., BLU-IGS, Orthokey, Lewes, Delaware, USA; OrthoPilot, B. Braun Aesculap, Tuttlingen, Germany; Medivision Surgelics System, Praxim, La Trouche, France). Image-based systems require anatomical reference data obtained from intraoperative fluoroscopy imaging. Image-free systems require no preoperative data, as they are able to acquire anatomical landmark and knee kinematics information. Image-free systems have been used for ACL reconstruction for more than 10 years. This system uses infrared cameras and transmitters with reflective markers attached to the femur and tibia to register the precise location of the instruments in three-dimensional (3D) space. The cameras can track the position of the instruments to within <1 mm and <1° with assistance from a computer [7, 54]. At the first step of registration, bony landmarks (consisting of the tibial tuberosity, anterior edge of the tibia, and the medial and lateral points of the tibial plateau) and knee kinematics (consisting of the knee position at 0° and 90° of knee flexion and consecutive knee positions between 0° and 90°) are registered (Fig. 41.1).

Next, the navigation computer builds a three-dimensional model of the knee joint. The intra-articular landmarks (consisting of the anterior horn of lateral meniscus, tibial and femoral footprint of the ACL, anterior notch outlet, etc.) are necessary for the computation of the tibial and femoral tunnel aperture. Surgeons can visualize the tibial and femoral tunnel position on the navigation display, as well as other valuable parameters necessary for creating a suitable tunnel such as the angle of the tibial tunnel in the sagittal and coronal planes, distance to the PCL anterior edge, distance to the posterior cartilage border of the lateral femoral condyle, distance between tunnels in the double-bundle technique, etc. (Fig. 41.2).

Additionally, knee stability test can be performed before and after graft fixation, to quantify surgical results, including the pivot shift (PS) test (Fig. 41.3). In our experience, the additional time required for navigation surgery is approximately 5–10 min.

Fig. 41.1 Transmitters with reflective markers were fixed to the femur and tibia via a pin fixator. The *straight pointer* attached to another transmitter is used to register the intra- and extra-articular landmarks

Fig. 41.2 Screenshot showing the navigation of the tibial drill tunnel (*Left*) and the navigation of the femoral drill tunnel (*Right*)

Fig. 41.3 Quantification of the PS test before and after ACL reconstruction

41.3 Accuracy of Tunnel Placement in ACL Reconstruction

The main object of using the navigation system for ACL reconstruction is to improve the precision of the femoral and tibial tunnel position. Several studies compared the accuracy of the tunnel position between navigation surgery and manual surgery. Regarding the tibial tunnel position, the mean position is not altered by the navigation systems but the deviation is significantly decreased [22, 47]. As for femoral tunnel placement, most studies show improved positioning in navigation-assisted ACL reconstruction on radiographic evaluation [22, 42, 46, 48]. Schep et al. studied intersurgeon variance during computer-assisted planning of ACL reconstruction and showed that the tunnel position was not associated with the experience level of the surgeon when using the computer-assisted surgical system [47].

There are few studies on the use of navigation systems in revision surgery [37, 51]. In revision surgery for failed ACL reconstruction, there are several types of problems including bone defects, primary tunnel malposition, and preexisting hardware. Creating an adequate new femoral tunnel is difficult in revision ACL surgery because of the existence of the primary tunnel. Taketomi et al. reported that 3D fluoroscopy-based navigation systems are especially helpful in this regard, because they enable visualization of the entire previous tunnel or any preexisting hardware inside the femoral tunnel that is not visible arthroscopically [51].

Recently, preservation of the ACL remnant has been a focus of ACL reconstruction. Remnant preservation is expected to accelerate graft maturation. However, it is difficult to confirm the ACL femoral footprint because of abundant remnant tissue. In such situations, navigation systems may be utilized for confirming the ACL footprint of the intercondylar lateral wall and for creating an adequate tunnel in the ACL footprint. Taketomi et al. described the femoral socket locations that were considered to be an anatomical footprint in accordance with previous cadaveric studies in remnant-preserving ACL reconstruction using 3D fluoroscopy-based navigation systems [52].

41.4 Knee Laxity and Kinematics Measurement

Another important feature of navigation systems in ACL reconstruction surgery is the capability to perform intraoperative kinematic evaluation of the knee joint during ACL reconstruction.

CAOS system for translational and rotational joint laxities evaluation under stress has only been reported since 2005. Zaffagnini et al. [56] and Martelli et al. [31] used the navigation for an in vivo setup with a high intersurgeon and intrasurgeon repeatability of the maneuvers.

With this system, many tests can be performed and measured for evaluating both static and dynamic instability at the operating room, before and after ACL reconstruction.

The static stability corresponds with uniplanar laxity (translation or rotation) at determined degree of flexion, for example, anteroposterior translation at 30° and 90° (Lachman and anterior drawer test, respectively), while dynamic corresponds to a complex combination of translation and rotation during the range of motion.

Since the development of new and easier navigation systems, the interest in computer-assisted procedures for clinical outcomes and research was increased. Many studies have been published since the 2000s to describe knee kinematics to enhance the knowledge about it and the effect of different techniques achieving static and dynamic stability.

Today, the most important clinical exam evaluating dynamic instability of the knee is the pivot shift test. For this reason, interest in navigating the PS was increased in the last years. Such test has been decomposed in many parameters; the most important are related with the translation, rotation, and acceleration of the lateral tibial plateau when the pivot shift maneuver is performed [28].

Some authors have used the navigation system in order to document the pre-operatory status and compared it with the surgical results of different techniques in ACL reconstruction surgery. Signorelli et al. in 2013 have shown the importance of preoperative measurements, especially in very unstable knees, in order to suspect secondary restraint lesions. In fact, higher level of preoperative laxities can underline complex injuries, where the isolated ACL reconstruction is not able to restore normal kinematics, and the addition of others procedures may be necessary to gain a better stabilization [49].

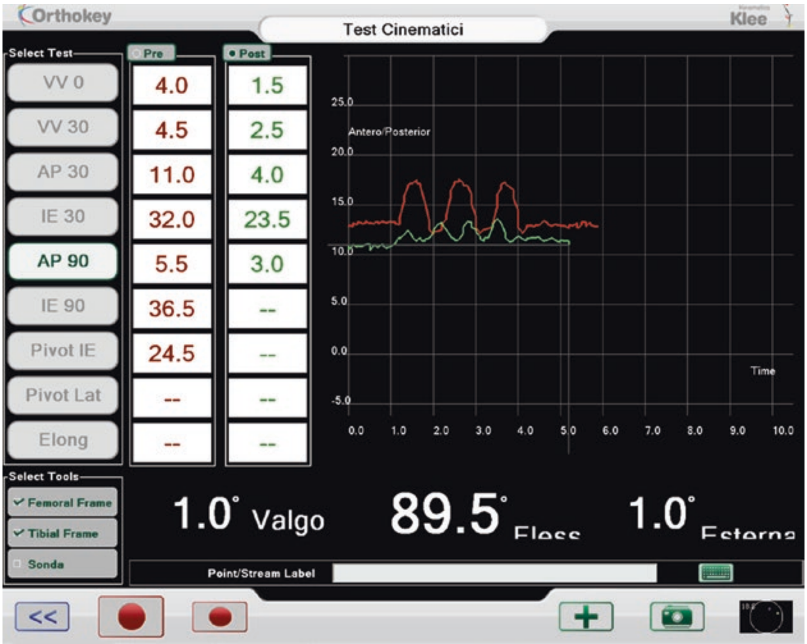
Others have used this system to assess physiological contralateral knee stability before ACL reconstruction. In the 2009, Miura and colleagues were the first to perform an in vivo study comparing both contralateral uninjured knee and ACL-injured knee [34].

More recently, Imbert et al. evaluated 32 patients who underwent ACL reconstruction surgery. They also compared with the contralateral uninjured joint. In clinical practice, both knees have always been evaluated, but in a qualitative way. These studies concluded that is important to evaluate objectively the healthy knee before surgery. Quantifying patient's physiological stability is very helpful for a better surgical approach [15].

41.5 Intraoperative Protocol

Usually navigation system is moved into the operating room and is placed about 2 m away from the operating table, after sterile field is prepared. Surgery is performed as usual, and only after graft is harvested, the tracking systems are fixed into the bones (tibia and femur) and then anatomical landmarks are acquired.

After that, different maneuvers are performed. Software used for kinematic acquisition (KLEE; Orhokey, Lewes, Delaware, USA) evaluates AP



Select Test	Pre	Post
VV 0	4.0	1.5
VV 30	4.5	2.5
AP 30	11.0	4.0
IE 30	32.0	23.5
AP 90	5.5	3.0
IE 90	36.5	--
Pivot IE	24.5	--
Pivot Lat	--	--
Elong	--	--

Fig. 41.4 Software interface (Klee, Orthokey) for intraoperative laxity evaluation. *Red curves* correspond with preoperative values and *green* with postoperative measures

translation at 30° and 90° (Lachman and anterior drawer test), VV (varus-valgus) rotation at 0° and 30°, IE (internal-external) rotation at 30° and 90°, and the pivot shift test. Maneuvers are performed and measured twice, before and after graft fixation (Fig. 41.4).

Finally when data is collected, the tracking frames are removed and surgery continues normally. Measurements displayed on screen are valuable information for the surgeon about the stabilizer effect of the surgical technique just performed (Fig. 41.5).

It is well known that the anteroposterior translation can be controlled by many different techniques, but achieving it hasn't to be the main objective in ACL surgeries, because rotational instability may persist [53, 57, 59].

Literature has shown for many years that the rotational stabilization is the principal goal when we face to unstable knees. In fact the presence of a positive pivot shift test can predict the failure of surgery [19, 23, 25, 45].

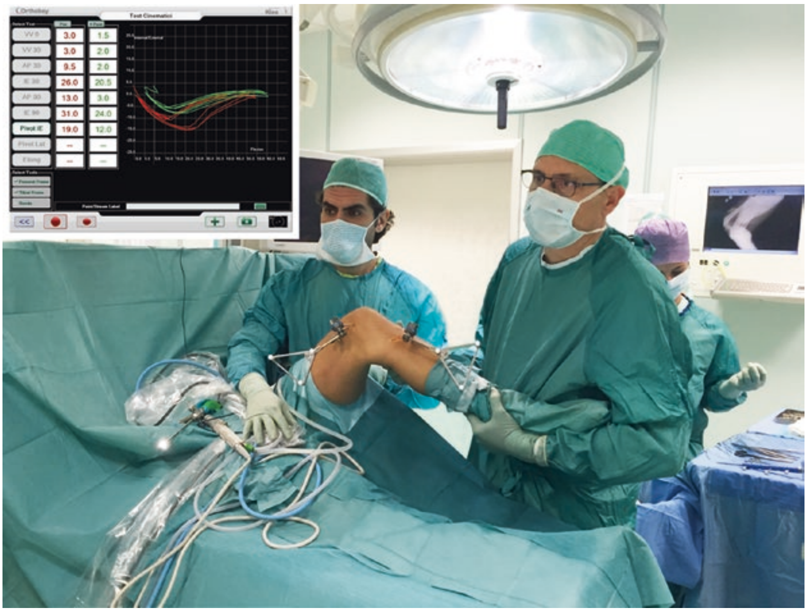
Concerning research applications, the navigation system allows to evaluate different reconstruction techniques.

Most of the studies reported the stabilizing effect of double-bundle ACL reconstruction, functionality of each bundle in the reconstructed ACL, quantification of the pivot shift phenomenon, and biomechanical function of ACL remnants, using a navigation system [4, 10, 14, 16–18, 20, 24, 26, 27, 29, 30, 34, 38, 39, 41, 44, 50, 55, 56, 60].

Ishibashi et al. reported that the posterolateral bundle (PLB) plays an important role in the extension position of the knee and that the anterolateral bundle (AMB) is more important in the flexion position [16].

In a recent systematic review performed by Björnsson et al. [3], they have found an important number of navigated studies comparing the stability achieved between anatomic double bundle and anatomic single bundle. Seventeen studies have compared the results in sagittal plane and they didn't find significant differences between them.

For the rotational instability, navigated analysis was performed in 20 studies and that only has shown a tendency supporting that DB is superior to control rotational instability. Further, comparisons were performed between anatomic



VV 0	3.0	1.5
VV 30	3.0	2.0
AP 30	9.5	2.0
IE 30	26.0	20.5
AP 90	13.0	3.0
IE 90	31.0	24.0
Pivot IE	19.0	12.0
Pivot Lat	--	--
Elong	--	--

Fig. 41.5 Real-time pivot shift comparison between preoperative laxity and the achieved stability

and nonanatomic double-bundle techniques, and they found that nonanatomic double bundle has similar effect in controlling anteroposterior translation and the PS test than the anatomical technique [60].

Navigation was also used to evaluate the addition of a lateral extra-articular plasty (LEAP). This procedure has been proposed for better control dynamic instability, because it has better biomechanical properties in terms of rotational stabilization.

Colombet et al., Monaco et al., and Zaffagnini et al, using similar reconstruction techniques, analyzed the rotational controlling effect of the addition of LEAP to the intra-articular ACL reconstruction. They measured translation and rotation in different surgical times: before surgery, between the fixation of the intra-articular graft and the LEAP, and a last measure when the surgery had finished [2, 6, 36].

The studies comparing the addition of LEAP to the single-bundle techniques have shown an increased control in translation and rotation especially in the lateral compartment. There are statistically significant differences in the anterior translation of the lateral compartment at 90° of flexion and less lateral compartment opening in valgus at 0–30° of flexion when a LEAP was added.

Related with rotational stability, Zaffagnini et al. showed that single-bundle reconstruction with the addition of LEAP controls better the internal and the external rotation at 90° of flexion, whereas Monaco et al. only reported better results when measuring internal rotation, but no significant difference in external rotation [11, 35, 58].

That is confirmed by the systematic review performed this year by Hewison et al. [13] in which they analyzed the effect of LEAP in 29 articles. They also showed statistically significant reduction in pivot shift in favor of the combined procedure.

Despite all the studies performed, we are still having controversies about which is the best technique controlling dynamic instability of the injured knee.

Navigation is considered the gold standard for laxity quantification, and validation of new noninvasive devices must be related to it, because it has demonstrated to be highly precise and reliable quantifying knee laxity after ACL injury.

One of the main advantages is that it allows a real-time quantitative evaluation of the knee conditions at different moments of the surgical procedure, and therefore it allows surgeons to evaluate the knee status during kinematic maneuvers and, with this information given, perform a better and individualized approach.

However, navigation systems are difficult to use in clinical practice because of the invasive nature of the transmitter attachment. To gain wider acceptance of the navigation system in the clinic as a measurement tool of knee stability and kinematics, noninvasive surface markers and the development of dedicated software are also desirable.

41.6 Clinical Results of Navigation-Assisted ACL Reconstruction

The navigation system can improve clinical outcomes and decrease the failure rate of ACL reconstruction by reducing the variability of the tunnel position and creating more accurate femoral and tibial tunnels.

There were five randomized controlled studies that compared navigation-assisted and conventional ACL reconstruction [5, 12, 32, 33, 43] (Table 41.1).

Eggerding et al. [9] reviewed and combined the results of the above studies and did not find statistically or clinically significant differences between navigation-assisted and conventional surgery as determined by IKDC subjective score, Lysholm score, Tegner activity score, knee stability, tunnel placement, or complications. Apart from a significantly increased operative time for randomized participants using the navigation system (between 9.3 and 27 min longer), there was no difference in outcome of navigation versus conventional ACL reconstruction. They concluded that the currently available evidence does not indicate any improvement in clinical outcome when using navigation systems.

Conclusion

Experienced surgeons are skilled in accurate placement of bone tunnels into the native ACL footprint by using a variety of intra-articular landmarks (such as the resident's ridge) as reference points without employing navigation systems. Furthermore, randomized trials of ACL reconstruction with or without navigation systems have shown that the clinical outcomes were not significantly different between the two groups. When using the navigation system, it should be noted that placement of the reference markers requires additional incisions, and complications such as fracture, wound infection, and skin necrosis may occur. Therefore, some surgeons are of the opinion that the use of navigation in ACL reconstruction is not worthwhile. However, navigation systems can provide surgeons with a wide variety of data in real time that cannot be obtained under arthroscopic observation. Additionally, navigation systems are useful for the objective assessment of the tunnel position and for the measurement of knee stability and kinematics of pre- and postoperative surgery. They also serve as an educational tool for less experienced surgeons. Recent developments in computer technology will likely lead to further improvements in navigation systems. Because they allow a wide variety of intraoperative data to be collected, the utility of navigation systems in research is also expected to expand.

References

1. Bargar WL, Bauer A, Borner M (1998) Primary and revision total hip replacement using the robodoc system. Clin Orthop Relat Res 354:82–91
2. Bignozzi S, Zaffagnini S, Lopomo N, Martelli S, Iacono F, Marcacci M (2009) Does a lateral plasty control coupled translation during antero-posterior stress in single-bundle ACL reconstruction? An in vivo study. Knee Surg Sports Traumatol Arthrosc 17:65–70. doi:10.1007/s00167-008-0651-6
3. Björnsson H, Desai N, Musahl V, Alentorn-Geli E, Bhandari M, Fu F, Samuelsson K (2015) Is double-bundle anterior cruciate ligament reconstruction superior to single-bundle? A comprehensive systematic review. Knee Surg Sports Traumatol Arthrosc 23(3):696–739. doi:10.1007/s00167-013-2666-x, Epub 2013 Sep 15
4. Brophy RH, Voos JE, Shannon FJ et al (2008) Changes in the length of virtual anterior cruciate ligament fibers during stability testing: a comparison of conventional single-bundle reconstruction and native anterior cruciate ligament. Am J Sports Med 36:2196–2203

5. Chouteau J, Benareau I, Testa R et al (2008) Comparative study of knee anterior cruciate ligament reconstruction with or without fluoroscopic assistance: a prospective study of 73 cases. Arch Orthop Trauma Surg 128:945–950
6. Colombet P (2011) Knee laxity control in revision anterior cruciate ligament reconstruction versus anterior cruciate ligament reconstruction and lateral tenodesis clinical assessment using computer-assisted navigation. Am J Sports Med 39:1248
7. Degenhart M (2004) Computer-navigated ACL reconstruction with the OrthoPilot. Surg Technol Int 12:245–251
8. Dessenne V, Lavallee S, Julliard R et al (1995) Computer-assisted knee anterior cruciate ligament reconstruction: first clinical tests. J Image Guid Surg 1:59–64
9. Eggerding V, Reijman M, Scholten RJ, Verhaar JA, Meuffels DE (2014) Computer-assisted surgery for knee ligament reconstruction. Cochrane Database Syst Rev 9:CD007601
10. Ferretti A, Monaco E, Labianca L et al (2009) Double-bundle anterior cruciate ligament reconstruction: a comprehensive kinematic study using navigation. Am J Sports Med 37:1548–1553
11. Ferretti A, Monaco E, Vadala A (2014) Rotatory instability of the knee after ACL tear and reconstruction. J Orthop Traumatol 15:75–79. doi:10.1007/s10195-013-0254-y
12. Hart R, Krejzla J, Svab P, Kocis J, Stipcak V (2008) Outcomes after conventional versus computer-navigated anterior cruciate ligament reconstruction. Arthroscopy 24:569–578
13. Hewison CE, Tran MN, Kaniki N et al (2015) Lateral Extra-articular tenodesis reduces rotational laxity when combined with anterior cruciate ligament reconstruction: A systematic review of the literature. Arthroscopy 31:2022–2034
14. Hofbauer M, Valentin P, Kdolsky R et al (2010) Rotational and translational laxity after computer-navigated single- and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18:1201–1207
15. Imbert P, Belvedere C, Leardini A (2014) Human knee laxity in ACL-deficient and physiological contralateral joints: intra-operative measurements using a navigation system. Biomed Eng Online 13:86. doi:10.1186/1475-925X-13-86
16. Ishibashi Y, Tsuda E, Tazawa K, Sato H, Toh S (2005) Intraoperative evaluation of the anatomical double-bundle anterior cruciate ligament reconstruction with the OrthoPilot navigation system. Orthopedics 28:s1277–s1282
17. Ishibashi Y, Tsuda E, Fukuda A, Tsukada H, Toh S (2008) Intraoperative biomechanical evaluation of anatomic anterior cruciate ligament reconstruction using a navigation system: comparison of hamstring tendon and bone-patellar tendon-bone graft. Am J Sports Med 36:1903–1912
18. Ishibashi Y, Tsuda E, Yamamoto Y, Tsukada H, Toh S (2009) Navigation evaluation of the pivot-shift phenomenon during double-bundle anterior cruciate ligament reconstruction: is the posterolateral bundle more important? Arthroscopy 25:488–495
19. Jonsson H, Riklund-Ahlström K, Lind J (2004) Positive pivot shift after ACL reconstruction predicts later osteoarthrosis: 63 patients followed 5–9 years after surgery. Acta Orthop Scand 75(5):594–599
20. Kanaya A, Ochi M, Deie M et al (2009) Intraoperative evaluation of anteroposterior and rotational stabilities in anterior cruciate ligament reconstruction: lower femoral tunnel placed single-bundle versus double-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc 17:907–913
21. Kendoff D, Citak M, Voos J, Pearle AD (2009) Surgical navigation in knee ligament reconstruction. Clin Sports Med 28:41–50
22. Klos TV, Habets RJ, Banks AZ et al (1998) Computer assistance in arthroscopic anterior cruciate ligament reconstruction. Clin Orthop Relat Res 354:65–69
23. Kocher MS, Steadman JR, Briggs KK, Sterett WI, Hawkins RJ (2004) Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. Am J Sports Med 32(3):629–634
24. Lane CG, Warren RF, Stanford FC, Kendoff D, Pearle AD (2008) In vivo analysis of the pivot shift phenomenon during computer navigated ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 16:487–492
25. Leitze Z, Losee RE, Jokl P, Johnson TR, Feagin JA (2005) Implications of the pivot shift in the ACL-deficient knee. Clin Orthop Relat Res 436:229–236
26. Lopomo N, Bignozzi S, Martelli S et al (2009) Reliability of a navigation system for intra-operative evaluation of antero-posterior knee joint laxity. Comput Biol Med 39:280–285
27. Lopomo N, Zaffagnini S, Bignozzi S, Visani A, Marcacci M (2010) Pivot-shift test: analysis and quantification of knee laxity parameters using a navigation system. J Orthop Res 28:164–169
28. Lopomo N, Zaffagnini S, Amis AA (2013) Quantifying the pivot shift test: a systematic review. Knee Surg Sports Traumatol Arthrosc 21:767–783
29. Lopomo N, Signorelli C, Bonanzinga T et al (2014) Can rotatory knee laxity be predicted in isolated anterior cruciate ligament surgery? Int Orthop 38:1167–1172
30. Maeda S, Ishibashi Y, Tsuda E, Yamamoto Y, Toh S (2011) Intraoperative navigation evaluation of tibial translation after resection of anterior cruciate ligament remnants. Arthroscopy 27:1203–1210
31. Martelli S, Zaffagnini S, Bignozzi S et al (2007) KIN-Nav navigation system for kinematic assessment in anterior cruciate ligament reconstruction: features, use, and perspectives. Proc Inst Mech Eng [H] 221:725–737
32. Mauch F, Apic G, Becker U, Bauer G (2007) Differences in the placement of the tibial tunnel dur-

ing reconstruction of the anterior cruciate ligament with and without computer-assisted navigation. Am J Sports Med 35:1824–1832

33. Meuffels DE, Reijman M, Verhaar JA (2012) Computer-assisted surgery is not more accurate or precise than conventional arthroscopic ACL reconstruction: a prospective randomized clinical trial. J Bone Joint Surg Am 94:1538–1545
34. Miura K, Ishibashi Y, Tsuda E et al (2010) Intraoperative comparison of knee laxity between anterior cruciate ligament-reconstructed knee and contralateral stable knee using navigation system. Arthroscopy 26:1203–1211
35. Monaco E, Labianca L, Conteduca F, De Carli A, Ferretti A (2007) Double bundle or single bundle plus extraarticular tenodesis in ACL reconstruction? A CAOS study. Knee Surg Sports Traumatol Arthrosc 15(10):1168–1174
36. Monaco E, Maestri B, Conteduca F, Mazza D, Iorio C, Ferretti A (2014) Extra-articular ACL reconstruction and pivot shift: in vivo dynamic evaluation with navigation. Am J Sports Med 42(7):1669–1674. doi:10.1177/0363546514532336
37. Nakagawa T, Hiraoka H, Fukuda A et al (2007) Fluoroscopic-based navigation-assisted placement of the tibial tunnel in revision anterior cruciate ligament reconstruction. Arthroscopy 23:5
38. Nakamae A, Ochi M, Deie M et al (2010) Biomechanical function of anterior cruciate ligament remnants: how long do they contribute to knee stability after injury in patients with complete tears? Arthroscopy 26:1577–1585
39. Nakase J, Toratani T, Kosaka M, Ohashi Y, Tsuchiya H (2013) Roles of ACL remnants in knee stability. Knee Surg Sports Traumatol Arthrosc 21:2101–2106
40. Nolte LP, Visarius H, Arm E et al (1995) Computer-aided fixation of spinal implants. J Image Guid Surg 1:88–93
41. Pearle AD, Solomon DJ, Wanich T et al (2007) Reliability of navigated knee stability examination: a cadaveric evaluation. Am J Sports Med 35: 1315–1320
42. Picard F, DiGioia AM, Moody J et al (2001) Accuracy in tunnel placement for ACL reconstruction. Comparison of traditional arthroscopic and computer-assisted navigation techniques. Comput Aided Surg 6:279–289
43. Plaweski S, Cazal J, Rosell P, Merloz P (2006) Anterior cruciate ligament reconstruction using navigation: a comparative study on 60 patients. Am J Sports Med 34:542–552
44. Plaweski S, Grimaldi M, Courvoisier A, Wimsey S (2011) Intraoperative comparisons of knee kinematics of double-bundle versus single-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 19:1277–1286
45. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD (2005) Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. Arthroscopy 21:1323e1329
46. Sati M, Staubli H, Bourquin Y, Kunz M, Nolte LP (2002) Real-time computerized in situ guidance system for ACL graft placement. Comput Aided Surg 7:25–40
47. Schep NW, Stavenuiter MH, Diekerhof CH et al (2005) Intersurgeon variance in computer-assisted planning of anterior cruciate ligament reconstruction. Arthroscopy 21:942–947
48. Shafizadeh S, Balke M, Wegener S et al (2011) Precision of tunnel positioning in navigated anterior cruciate ligament reconstruction. Arthroscopy 27:1268–1274
49. Signorelli C, Bonanzinga T, Lopomo N, Marcheggiani Muccioli GM, Bignozzi S, Filardo G, Zaffagnini S, Marcacci M (2013) Do pre-operative knee laxity values influence post-operative ones after anterior cruciate ligament reconstruction? Scand J Med Sci Sports 23:e219–e224
50. Song EK, Oh LS, Gill TJ et al (2009) Prospective comparative study of anterior cruciate ligament reconstruction using the double-bundle and single-bundle techniques. Am J Sports Med 37:1705–1711
51. Taketomi S, Inui H, Nakamura K et al (2012) Three-dimensional fluoroscopic navigation guidance for femoral tunnel creation in revision anterior cruciate ligament reconstruction. Arthrosc Tech 1(1):e95–e99. doi:10.1016/j.eats.2012.04.003
52. Taketomi S, Inui H, Sanada T et al (2014) Remnant-preserving anterior cruciate ligament reconstruction using a three-dimensional fluoroscopic navigation system. Knee Surg Relat Res 26:168–176
53. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32(4):975–983
54. Tsuda E, Ishibashi Y, Fukuda A, Tsukada H, Toh S (2007) Validation of computer-assisted double-bundle anterior cruciate ligament reconstruction. Orthopedics 30:S136–S140
55. Yamamoto Y, Ishibashi Y, Tsuda E et al (2010) Comparison between clinical grading and navigation data of knee laxity in ACL-deficient knees. Sports Med Arthrosc Rehabil Ther Technol 2:27
56. Zaffagnini S, Bignozzi S, Martelli S, Imakiire N, Lopomo N, Marcacci M (2006) New intraoperative protocol for kinematics evaluation of ACL reconstruction: preliminary results. Knee Surg Sports Traumatol Arthrosc 14:811–816
57. Zaffagnini S, Bignozzi S, Martelli S, Lopomo N, Marcacci M (2007) Does ACL reconstruction restore knee stability in combined lesions? An in vivo study. Clin Orthop Relat Res 454:95–99
58. Zaffagnini S, Signorelli C, Lopomo N, Bonanzinga T, Marcheggiani Muccioli GM, Bignozzi S, Visani A, Marcacci M (2011) Anatomic double-bundle and over-the-top single-bundle with additional extra-articular tenodesis: an in vivo quantitative assessment

of knee laxity in two different ACL reconstructions. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-011-1589-7

59. Zaffagnini S, Bonanzinga T, Marcheggiani Muccioli GM, Giodano G, Bruni D, Bignozzi S, Lopomo N, Marcacci M (2011) Does chronic medial collateral ligament laxity influence the outcome of anterior cruciate ligament reconstruction? A prospective evaluation with a minimum three-year follow-up. J Bone Joint Surg (Br) 93(8):1060–1064. doi:10.1302/0301-620X.93B8.26183
60. Zaffagnini S, Marcheggiani Muccioli GM, Signorelli C, Lopomo N, Grassi A, Bonanzinga T, Nitri M, Marcacci M (2014) Anatomic and nonanatomic double-bundle anterior cruciate ligament reconstruction: an in vivo kinematic analysis. Am J Sports Med 42(3):708–715. doi:10.1177/0363546513519070, Epub 2014 Feb 11

42

Considerations for Treatment of Concomitant Cartilage and ACL Injury

Jan Harald Røtterud and Lars Engebretsen

42.1 Introduction

The combination of ACL injury and cartilage lesions is a serious injury to the knee. Even though not as common as concomitant meniscal lesions, cartilage lesions (International Cartilage Repair Society [ICRS] grades 1–4) [6, 7] are found in approximately 27 % of ACL-injured knees at the time of ACL reconstruction [25]. It has been shown that the presence of a focal full-thickness cartilage lesion ([ICRS] grades 3–4) at the time of ACL reconstruction leads to impaired short- and midterm patient-reported outcome [9, 24, 26] and an increased risk of later OA [17, 19]. The combination of concomitant cartilage lesions being a common finding and a predictor of poorer outcome requires that ACL surgeons have a well-founded strategy for treating these cartilage lesions.

42.2 Treatment Decision-Making

There are several factors that have to be considered when deciding the treatment strategy for a concomitant cartilage lesion. At first, it must be assessed whether the cartilage lesion is symptomatic or not. This can be difficult, as the clinical picture presented by the patients will be a mixture of symptoms from the ACL injury, the cartilage lesion, and other possible concomitant injuries. Pain and swelling are the most common symptoms from cartilage lesions. Furthermore, episodes of locking and catching might be present. However, cartilage lesions can also be asymptomatic or present with more vague symptoms. Hence, it can be difficult to distinguish ACL-injured patients with symptomatic cartilage lesions from patients with asymptomatic lesions [13, 16].

If the cartilage lesion is considered as symptomatic, further considerations must include whether the cartilage lesion itself and the patient are suited for a surgical cartilage procedure or not. Several factors are associated with the outcome after cartilage surgery, and the outcome is also related to the type of surgery [3, 4, 20]. Factors related to the cartilage lesion are size, depth, and location of the lesion. Patient factors include sex, age, body mass index, activity level, concomitant injuries, and knee alignment.

In general, a cartilage lesion present at the time of ACL reconstruction can either be left untreated or treated surgically. If left untreated at the time of ACL reconstruction, observation, rehabilitation, and surgical treatment at a later stage are further options. The option of nonoperative treatment by rehabilitation of patients with

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Table 42.1 Adjusted effects of no treatment, debridement, and microfracture of concomitant full-thickness cartilage lesions (ICRS grades 3–4) on the Knee Injury and Osteoarthritis Outcome Score (KOOS) at 2-year follow-up after ACL reconstruction

		Debridement			Microfracture		
KOOS subscales	*N*	β	95 % CI	*p*	β	95 % CI	*p*
Pain	332	0.1	(−4.2 to 4.5)	ns	−4.2	(−8.6 to 0.2)	ns
Symptoms	335	1.0	(−3.8 to 5.7)	ns	−3.3	(−8.2 to 1.5)	ns
ADL	333	1.8	(−2.1 to 5.7)	ns	−2.7	(−6.6 to 1.2)	ns
Sport/rec	334	−0.2	(−7.9 to 7.5)	ns	−8.6	(−16.4 to −0.7)	0.032
QoL	335	2.1	(−4.3 to 8.4)	ns	−7.2	(−13.6 to −0.8)	0.028

Adjusted for gender, age, previous ipsilateral knee surgery, time from injury to surgery, concomitant ligament injury, concomitant meniscal lesion(s), meniscus resection, type of ACL graft, area of cartilage lesion, depth (ICRS grade) of cartilage lesion, location of cartilage lesion, and preoperative KOOS scores

No treatment of cartilage lesions used as reference

ADL activities in daily living, *QoL* quality of life, *N* number of patients included in the regression analyses, *β* regression coefficient, *CI* confidence interval, *p* level of significance, *ns* not significant

focal cartilage lesions has been subject to few studies. Some evidence exists in the literature that rehabilitation might have a positive effect on cartilage metabolism and outcomes in patients with focal cartilage lesions [14, 23, 28].

Regarding surgical treatment of concomitant cartilage lesions in ACL-injured knees, all surgical treatment options described for isolated cartilage lesions are alternatives. However, even though an extensive amount of literature have been published on surgical treatment of isolated cartilage lesions, few previous high-quality studies have focused primarily on the treatment of concomitant cartilage lesions in ACL-injured knees [8]. Regardless if ACL reconstruction has been carried out or not, an ACL injury alters the biomechanics and biochemistry of the knee joint, which in turn can affect the outcome of cartilage surgery. Hence, knowledge from studies on treatment of isolated focal cartilage lesions cannot necessarily be generalized to ACL-injured patients.

Drilling, microfracture, periosteal flap transplantation, osteochondral autologous transplantation, and autologous chondrocyte implantation of cartilage lesions in combination ACL reconstruction have shown acceptable and promising results in the previous literature [1, 2, 5, 10, 15, 18, 21, 22]. However, these studies have been case-series or case-control studies with relatively small numbers of patients included in the different treatment groups, making it difficult to conclude and generalize about the treatment of choice. The only randomized trial on concomitant treatment of cartilage lesions and ACL reconstruction is a recent study by Gudas et al. [12], which compared patients receiving debridement, microfracture, and osteochondral autologous transplantation of concomitant cartilage lesions at 3-year follow-up after ACL reconstruction. Gudas et al. found that patients treated with osteochondral autologous transplantation reported significantly better outcome by the IKDC subjective scores than patients treated with microfracture or debridement and that there were no significant differences between the patients treated with microfracture and debridement. However, Gudas et al. did not include a control group of patients with cartilage lesions left untreated, so it is difficult to evaluate the actual treatment effect. In a recent cohort study from the Norwegian and Swedish National Knee Ligament Registries, our group evaluated 357 patients with concomitant full-thickness cartilage lesions with KOOS at 2-year follow-up after ACL reconstruction [27]. In Scandinavia, the majority of concomitant cartilage lesions in ACL-injured patients are either left untreated or treated by surgical debridement or microfracture [11].

We found that in comparison to leave the cartilage lesions untreated at the time of ACL reconstruction, MF showed adverse effects on patient-reported outcome (KOOS), and debridement showed no effects on patient-reported outcome (Table 42.1) [27]. Hence, we suggested that microfracture of concomitant full-thickness cartilage lesions in ACL-injured knees should be performed restrictively.

42.3 Conclusions on Treatment Strategies

Since there is no evidence that surgical treatment of a concomitant cartilage lesion in ACL-injured knees will reduce the risk of later OA, surgical treatment of these cartilage lesions should be restricted to symptomatic lesions.

Even for symptomatic lesions, to date, none of the surgical treatment options for concomitant cartilage lesions in ACL-injured knees are proven to be superior compared to leaving these cartilage lesions untreated. Microfracture of concomitant full-thickness cartilage lesions in ACL-injured knees should probably be avoided until future studies have identified if there are any subgroups of patients that might benefit from microfracture of cartilage lesions at the time of ACL reconstruction.

Some selected ACL-injured patients that are well suited for cartilage surgery might benefit from surgical treatment of concomitant cartilage lesions. For unstable lesions, debridement is a simple and easy procedure to perform, which might relieve symptoms. However, current evidence suggests that no treatment of the cartilage lesions is a safe and sound first-line option in the majority of ACL-injured patients.

References

1. Alfredson H, Thorsen K, Lorentzon R (1999) Treatment of tear of the anterior cruciate ligament combined with localised deep cartilage defects in the knee with ligament reconstruction and autologous periosteum transplantation. Knee Surg Sports Traumatol Arthrosc 7:69–74
2. Amin AA, Bartlett W, Gooding CR, Sood M, Skinner JA, Carrington RW, Briggs TW, Bentley G (2006) The use of autologous chondrocyte implantation following and combined with anterior cruciate ligament reconstruction. Int Orthop 30:48–53
3. Behery O, Siston RA, Harris JD, Flanigan DC (2014) Treatment of cartilage defects of the knee: expanding on the existing algorithm. Clin J Sport Med 24:21–30
4. Bekkers JE, Inklaar M, Saris DB (2009) Treatment selection in articular cartilage lesions of the knee: a systematic review. Am J Sports Med 37(Suppl 1): 148S–155S
5. Bobic V (1996) Arthroscopic osteochondral autograft transplantation in anterior cruciate ligament reconstruction: a preliminary clinical study. Knee Surg Sports Traumatol Arthrosc 3:262–264
6. Brittberg M, Peterson L (1998) Introduction of an articular cartilage classification. ICRS Newsl 1:5–8
7. Brittberg M, Winalski CS (2003) Evaluation of cartilage injuries and repair. J Bone Joint Surg Am 85-A(Suppl 2):58–69
8. Brophy RH, Zeltser D, Wright RW, Flanigan D (2010) Anterior cruciate ligament reconstruction and concomitant articular cartilage injury: incidence and treatment. Arthroscopy 26:112–120
9. Cox CL, Huston LJ, Dunn WR, Reinke EK, Nwosu SK, Parker RD, Wright RW, Kaeding CC, Marx RG, Amendola A, McCarty EC, Spindler KP (2014) Are articular cartilage lesions and meniscus tears predictive of IKDC, KOOS, and Marx activity level outcomes after anterior cruciate ligament reconstruction? A 6-year multicenter cohort study. Am J Sports Med 42:1058–1067
10. Gaweda K, Walawski J, Weglowski R, Patyra M (2006) Rehabilitation after one-stage anterior cruciate reconstruction and osteochondral grafting. Int Orthop 30:185–189
11. Granan LP, Inacio MC, Maletis GB, Funahashi TT, Engebretsen L (2012) Intraoperative findings and procedures in culturally and geographically different patient and surgeon populations: an anterior cruciate ligament reconstruction registry comparison between Norway and the USA. Acta Orthop 83:577–582
12. Gudas R, Gudaite A, Mickevicius T, Masiulis N, Simonaityte R, Cekanauskas E, Skurvydas A (2013) Comparison of osteochondral autologous transplantation, microfracture, or debridement techniques in articular cartilage lesions associated with anterior cruciate ligament injury: a prospective study with a 3-year follow-up. Arthroscopy 29:89–97
13. Hjermundrud V, Bjune TK, Risberg MA, Engebretsen L, Årøen A (2010) Full-thickness cartilage lesion do not affect knee function in patients with ACL injury. Knee Surg Sports Traumatol Arthrosc 18:298–303
14. Hunt MA, Pollock CL, Kraus VB, Saxne T, Peters S, Huebner JL, Sayre EC, Cibere J (2013) Relationships amongst osteoarthritis biomarkers, dynamic knee joint load, and exercise: results from a randomized controlled pilot study. BMC Musculoskelet Disord 14:115
15. Imade S, Kumahashi N, Kuwata S, Kadowaki M, Tanaka T, Takuwa H, Uchio Y (2013) A comparison of patient-reported outcomes and arthroscopic findings between drilling and autologous osteochondral grafting for the treatment of articular cartilage defects combined with anterior cruciate ligament injury. Knee 20:354–359
16. Inacio MC, Chen Y, Maletis GB, Ake CF, Fithian DC, Granan LP (2014) Injury pathology at the time of anterior cruciate ligament reconstruction associations with self-assessment of knee function. Clin J Sport Med 24:461–467
17. Janssen RP, du Mée AW, van Valkenburg J, Sala HA, Tseng CM (2013) Anterior cruciate ligament reconstruction with 4-strand hamstring autograft and

accelerated rehabilitation: a 10-year prospective study on clinical results, knee osteoarthritis and its predictors. Knee Surg Sports Traumatol Arthrosc 21: 1977–1988

18. Klinger HM, Baums MH, Otte S, Steckel H (2003) Anterior cruciate reconstruction combined with autologous osteochondral transplantation. Knee Surg Sports Traumatol Arthrosc 11:366–371
19. Li RT, Lorenz S, Xu Y, Harner CD, Fu FH, Irrgang JJ (2011) Predictors of radiographic knee osteoarthritis after anterior cruciate ligament reconstruction. Am J Sports Med 39:2595–2603
20. Mithoefer K, Williams RJ III, Warren RF, Potter HG, Spock CR, Jones EC, Wickiewicz TL, Marx RG (2005) The microfracture technique for the treatment of articular cartilage lesions in the knee. A prospective cohort study. J Bone Joint Surg Am 87: 1911–1920
21. Osti L, Papalia R, Del BA, Amato C, Denaro V, Maffulli N (2010) Good results five years after surgical management of anterior cruciate ligament tears, and meniscal and cartilage injuries. Knee Surg Sports Traumatol Arthrosc 18:1385–1390
22. Peterson L, Minas T, Brittberg M, Nilsson A, Sjogren-Jansson E, Lindahl A (2000) Two- to 9-year outcome after autologous chondrocyte transplantation of the knee. Clin Orthop Relat Res 322:212–234
23. Røtterud JH, Reinholt FP, Beckstrøm KJ, Risberg MA, Årøen A (2014) Relationship between CTX-II and patient characteristics, patient-reported outcome, muscle strength, and rehabilitation in patients with a focal cartilage lesion of the knee: a prospective exploratory cohort study of 48 patients. BMC Musculoskelet Disord 15:99
24. Røtterud JH, Risberg MA, Engebretsen L, Årøen A (2012) Patients with focal full-thickness cartilage lesions benefit less from ACL reconstruction at 2–5 years follow-up. Knee Surg Sports Traumatol Arthrosc 20:1533–1539
25. Røtterud JH, Sivertsen EA, Forssblad M, Engebretsen L, Årøen A (2011) Effect of gender and sports on the risk of full-thickness articular cartilage lesions in anterior cruciate ligament-injured knees: a nationwide cohort study from Sweden and Norway of 15 783 patients. Am J Sports Med 39:1387–1394
26. Røtterud JH, Sivertsen EA, Forssblad M, Engebretsen L, Årøen A (2013) Effect of meniscal and focal cartilage lesions on patient-reported outcome after anterior cruciate ligament reconstruction: a nationwide cohort study from Norway and Sweden of 8476 patients with 2-year follow-up. Am J Sports Med 41:535–543
27. Røtterud JH, Sivertsen EA, Forssblad M, Engebretsen L, Årøen A (2015) Effect on patient-reported outcomes of debridement or microfracture of concomitant full-thickness cartilage lesions in anterior cruciate ligament-reconstructed knees: a nationwide cohort study from Norway and Sweden of 357 patients with 2-year follow-up. Am J Sports Med 44:337–344
28. Wondrasch B, Årøen A, Røtterud JH, Høysveen T, Bølstad K, Risberg MA (2013) The feasibility of a 3-month active rehabilitation program for patients with knee full-thickness articular cartilage lesions: the Oslo cartilage active rehabilitation and education study. J Orthop Sports Phys Ther 43:310–324

ACL Reconstruction and Progression of OA

43

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43.1 Introduction

Osteoarthritis can occur in young patients following intra-articular pathology such as rupture of the cruciate ligaments or a medial meniscectomy with varus malalignment. ACL deficiency creates a modification in the biomechanics of the knee with an alteration of the rolling-sliding motion. The presence of a meniscal lesion at the time of the injury or secondary to the laxity increases kinematic disorders and contributes to cartilage damage and osteoarthritis. Combined surgery-associated ACL reconstruction and HTO represent an interesting salvage procedure for such complex patients who are usually young and want relief for both pain and instability. After seeing knee modifications after ACL injury and the relation between ACL rupture and OA, we will deal with diagnostic and therapeutic strategy and present a systematic review of HTO with ACL reconstruction.

43.2 Knee Biomechanics After ACL Injury

Anterior cruciate ligament tear (ACLT) is a common knee injury and leads to osteoarthritis in roughly half of patients within 10 years [46, 47]. The high incidence and risk for premature, disabling OA after ACL injury have been consistently reported in athletes and nonathletes of both sexes. In young female soccer players with a mean age of 31, 82 % showed radiographic changes, 75 % had knee symptoms, and 51 % met criteria for radiographic OA just 12 years after ACL injury [48]. Comparable morbidity was also shown for male soccer players [49, 50]. Because the highest rates of ACL injury occur in teenagers and young adults [51–53], many will be affected during their prime years. While the overriding immediate concern is that ACL injury removes promising athletes from competing for at least a full season, the longer-term sequelae of joint degeneration and dysfunction are of greater concern. Current treatments to include ACL reconstruction and rehabilitation permit the majority of patients to recover sufficient knee function to return to work- and sports-related activities. Thus, reducing the risk for premature osteoarthritis after ACL injury and surgery is a clinical priority.

Joint injuries result in numerous and varied changes to the structural, biological, and biomechanical integrity of diarthrodial joints [54]. The

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structural changes to the ACL injured knee range from obvious tears to the ligament that are frequently accompanied by meniscus injuries along with bone edema representative of where the tibia impacted the femur shortly after failure of the ACL. Meniscus tears commonly occur after ACL injury and represent a significant structural change to the knee [55]. Arthroscopy and MRI can sometimes show incident and persistent injuries sustained by the articular cartilage at and surrounding these points of impact [56, 57].

In striving to understand the role of cartilage injury in premature OA after ACL tear, one seeming paradox has been that the bone bruises showing impact injury are typically to the lateral compartment [57, 58]. Yet, OA is more frequently observed to the medial compartment after ACL injury [59]. This suggests that other factors aside from acute structural changes to articular cartilage impact on OA progression after ACL injury. What is less obvious and often “invisible” to radiographs, conventional MRI, and arthroscopy are more subtle subsurface injuries and matrix changes to articular cartilage retaining intact surfaces occurring as a result of abnormal loading patterns and biochemical changes to the joint. These injuries can, however, be appreciated by histology, optical coherence tomography, and quantitative MRI [60, 61].

Quantitative MRI has been increasingly evaluated for its utility as a diagnostic tool to show subclinical injury to the articular cartilage after ACL injury [62–64]. The novel imaging technique of ultrashort echo time-enhanced T2* mapping has shown elevated MRI UTE-T2* signals reflective of matrix changes consistent with “bruising” of the deep tissue of still intact articular cartilage [61, 64, 65] after ACLT. Longitudinal MRI UTE-T2* evaluations of the same subjects 2 years later showed that the UTE-T2* signals decreased to a level comparable to that of uninjured controls in most but not all subjects [61]. This data suggests that deep, subsurface injuries to the medial knee cartilage observed acutely after ACL injury have a potential to heal in cartilage retaining intact articular surfaces. However, as this did not occur in all subjects, other factors also impact OA risk apart from cartilage injury.

43.2.1 Knee Biomechanics and Knee OA Progression

Changes to knee kinematics after ACL injury are substantial and have not been shown to be fully corrected after reconstructive surgery [66, 67]. Changes to rotation frequently remain leading to altered contact points on the cartilage surfaces even with low-demand activities such as walking [66]. When analyzed in relation to graft orientation, abnormal rotation after ACLR was related to non-anatomic vertical graft placements. As well, altered gait consisting of reduced knee extension at heel strike has also been observed after ACLR [66].

In the evolution of ACL reconstruction surgery, joint space narrowing is an important parameter to decide which surgical procedure to perform [1–3]. The classification of the International Knee Documentation Committee (IKDC) [3], for the evaluation of patient outcome, describes four stages of osteoarthritis: A (normal radiograph), B (remodeled joint without pinching), C (space narrowing of less than 50 %), and D with more than 50 % of joint space narrowing. Pre-osteoarthritis has a radiological definition. It was established in 1987 through a better knowledge of the natural history of osteoarthritis after anterior cruciate ligament injuries (ACL) [4, 5]. Four signs are important to relate an old ACL injury to osteoarthritis: redesign of osteophyte-intercondylar notch which closes progressively with a hook aspect of the tibial spines, femorotibial bicompartimental remodeling with a flattening of the condyles, posterior tibial osteophytes, and anterior subluxation of the tibial plateau on the lateral single leg weight-bearing view.

The ACL rupture induces a change in the kinematics of the knee with three main consequences: loss of control of the anterior tibial translation (primary restraint, an average of 3 mm), change in the knee rotation axis, and loss of synchronization between the lateral femoral condyle and the tibial plateau, leading to an anterior positive jerk test.

During gait, anterior tibial translation is a normal physiological phenomenon. It is facilitated by the contraction of the quadriceps. The first obstacle is the ACL, from 0° to 30°. After 30° of flexion, the ACL, the posterior segment of the medial

Table 43.1 Frequency of occurrence of osteoarthritis according to the medial meniscal status and anterior cruciate ligament

Medial meniscus and ACL	Osteoarthritis (%)
Medial meniscectomy/ACL-deficient knee nonreconstructed [18]	100
Medial meniscectomy/ACL reconstruction [15, 17, 19]	24–45
Medial meniscectomy/ACL intact [20]	16
Intact medial meniscus/ACL reconstruction [15, 17, 19]	4–11

meniscus, and the tibial slope counteract the anterior tibial translation. The secondary restraint to anterior tibial translation is the medial meniscus which functions as a rear bumper [2, 6, 7]. The occurrence of a meniscal tear is the key prognostic factor in the onset of osteoarthritis. Meniscal preservation remains the best way to prevent osteoarthritis [2, 8, 9]. The disappearance of the posterior wedge promotes an increase in anterior tibial translation, in constraints, and in posteromedial cartilage wear [1, 4]. Eventually, a posterior cup secondary to medial posterior wear appears and posterior tibial osteophytes develop in addition. The knee gradually deforms in varus after medial meniscectomy in the ACL-deficient knee [1, 4, 10]. Additional clinical factors are likely to contribute to the development of osteoarthritis. Frontal (genu varum) and sagittal (tibial slope) plane alignment are important [11]. Patient with preserved medial menisci has little osteoarthritis 10 years later [12–15]. The detrimental effect of meniscectomy is directly influenced by the time from injury to surgery [5, 16, 17]. However, the medial meniscectomy alone is not a sufficient condition, because in three studies review in Table 43.1, many patients who had a medial meniscectomy did not develop osteoarthritis. Meniscectomy remains the major prognostic factor for the occurrence of osteoarthritis in the long term (Table 43.1).

43.3 Diagnostic and Therapeutic Strategy

Several surgical treatment options are available in case of ACL injury and mild OA: anterior cruciate ligament reconstruction, isolated coronal plane realignment osteotomy, or in association with ACL graft, deflection osteotomy, and possible associated meniscal transplantation with ACL reconstruction. Evaluation of the patient and knee history is essential for surgical decision-making. The following parameters are relevant for indication: the patient's functional objectives, knee laxity evaluation, predominant symptom (pain, instability or both), meniscal status, and X-ray evaluation including long-leg axis.

The objectives of chronic anterior laxity treatment are:

- Stabilize the knee by removing the instability and protecting the menisci.
- Prevent osteoarthritis (as possible) and/or, hopefully, avoid osteoarthritis progression.

Several situations can arise depending on the Dejour laxity classification [1]. We summarized this classification and the therapeutic options in an algorithm (Fig. 43.1). According to the stage of osteoarthritis, treatment is based on a valgus or deflection osteotomy. Both corrections are sometimes combined, but one of the two correction planes must be favored over the other. Indication for osteotomy is malalignment with symptomatic osteoarthritis in the overloaded compartment. The analysis of alignment in both planes is essential (long-leg axis, measuring the tibial slope) for planning tibial osteotomy (frontal or coronal plane).

In the ACL-deficient knee with varus deformity, the biomechanical and surgical objective is to restore overcorrection to 3° of mechanical valgus, if ACL reconstruction is combined with HTO. Correction of the tibial slope may be proposed if anterior or posterior tibial translation is excessive or associated with a correction in the frontal plane.

In patients with a painful and unstable ACL-deficient knee with varus deformity, combined surgery including ACL reconstruction and HTO represents an interesting salvage procedure for such complex patients who are usually young and desire improvement in both their stability and pain (47 Chatain).

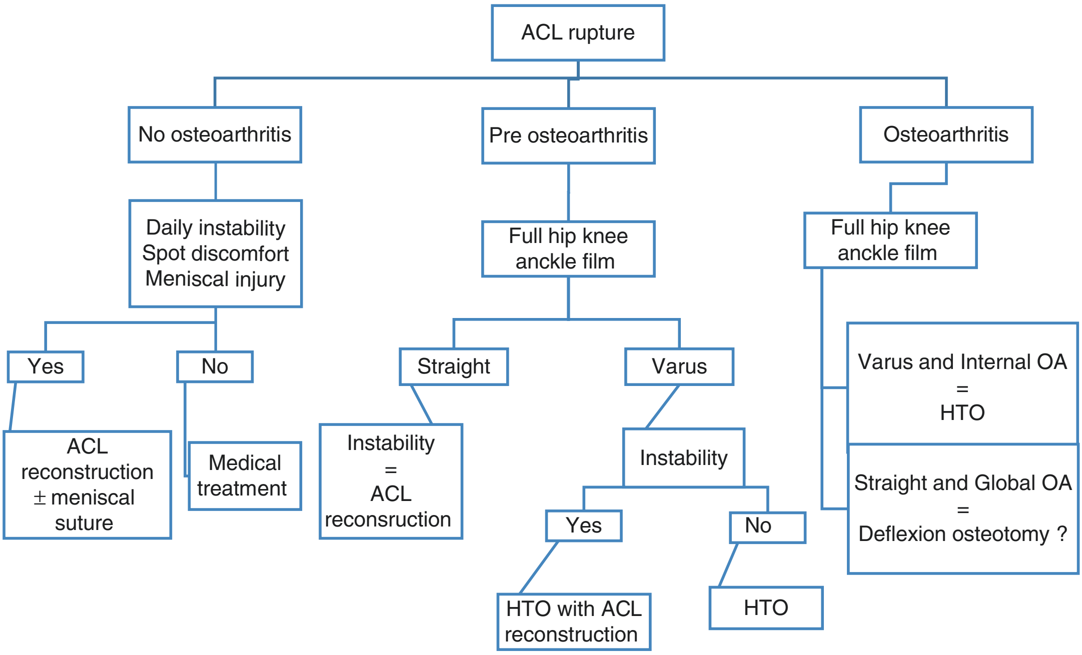

Fig. 43.1 Therapeutic options algorithm

43.4 Systematic Review

In the recent literature, only 21 publications of combined HTO and ACL reconstruction (either at the same stage or separately) have been published [42]. The main characteristics of the papers are summarized in Table 43.2. The number of patient in each series is very low from 5 to 51 cases, compared to the number of isolated ACL reconstruction during the same period. In most cases, these young patients (20–25 years old) were sportsmen and often competitors. Many had chronic anterior laxity with a former long delay between injury and surgery (more than 10 years). They also present severe cartilage damage, and during this period, a medial meniscectomy was very frequently observed from 56 to 100 % of medial meniscectomy. Zaffagnini [21] also report a high frequency of previous ACL reconstruction (40 %). The mean age of this study was 40.1 years; and was older than in other previous studies and the mean delay from injury to injury was longer 10.4 ± 8.1 years.

At the time of surgery, patients were active but present both knee pain and knee instability as objective by the instrumental laxity measurement. The main symptoms for indications were instability and medial pain. Radiographically, there was prearthritic change in most of the patients with joint space narrowing less than 50 %. There was a varus deformity with a global hip knee angle in varus (3.8 + 2.7° for Zaffagnini [21], 3° for Bonin [22, 23]. The results are interesting with low morbidity and low failure rate at femoral follow-up. With a mean 6.5 years of follow-up, the failure rate was 6 % for Zaffagnini [21] and two cases of stiffness for Bonin [22, 23]. For the ACL reconstruction, it was both intra-articular graft, and in some situation an extra-articular tenodesis was added to better pivot shift control. However, with the small number available, no statistical significant difference could be shown. An ACL procedure could be associated simultaneously as described by Elser [24]. Clinically, patients are satisfied or very satisfied in 80–90 % of cases. A significant number of active patients were able to resume sportive activity moderate (44–47 %) [7, 21–23]. Knee stability was found to be associated with improved symptoms of pain [10, 11, 22,

Table 43.2 Association of ACL reconstruction and high tibial osteotomy

Author	FU (years)	n	Age	% medial meniscectomy	Delay for surgery	Open wedge or closing osteotomy	Clinical results	Assessment of OA
Badhe and Forster [33]	2.8	14	34		8.3 years	10 F/4 O		
Boileau and Neyret [34]	4	58	28	73 %	5 years	51 C/7 O		
Bonin and Neyret [22, 23]	12	30	30	63 %	12 years	25 C/5O	IKDC: 78.5	IKDC C/D: 20
Boss et al. [35]	6.25	27	36	74 %		24 C/3 O	IKDC A/B : 18	
Boussaton and Potel [27]	6.5	51	36	78 %	9 years	51 C		
Dejour et al. [10]	3.6	44	29	61 %	6 years	37 C/7 O	91 % satisfied or very satisfied	
Demange et al. [36]		8	39.1			8 O		
Garin et al. [37]	3	18	36	77 %		13 C/5 O		
Imhoff et al. [38]	?	55	33					
Lattermann and Jakob [25]	5.8	27	37	92.5 %	8.3 years	17 C/10 O		IKDC C/D : 19
Lerat et al. [7]	5.9	51	37	86 %	9.5 years	39 C/12 O		
Neuschwander et al. [39]	2.5	5	27	100 %	7 years	7C	Lysholm: 88	
Noyes et al. [26]	4.5	41	29	73 %	6.5 years	41 C		
Noyes et al. [11]	4.5	41	32	93 %	10 years	41C	Cincinnati 63 – >82	
O’Neill and James [40]	3	10	32.1	100 %		10 C	IKDC: 67	
Zaffagnini et al. [21]	6.5	32	40.1	53 %	10 years	32 C	Tegner: 5 IKDC: 72	IKDC C/D: 24
Williams III et al. [41]	3.5	25	35.5	96 %		25 C		
Trojani et al. [43]	6	29	43			29 O	IKDC A/B: 70 % IKDC 77 23/29 sport return	IKDC C/D: 22
Akamatsu et al. [44]	2	4	45			4 O	Lysholm: 93.5	
Schuster et al. [45]	6	33	47			33 O + Microfracture	IKDC A/B: 17/22 IKDC 73.1	

23, 25, 26]. Factors associated with limitations in return to sports activities were long term between initial injury and surgery, multiple procedures, cartilage lesion, and residual laxity greater than 10 mm [27].

Pain relief was predictable (55–64 % of cases). The instability is well controlled: 78–90 % of negative Lachman and 88–96 % of negative pivot shift. For Bonin [22, 23], the overall results are significantly related to the importance of preoperative tibial translation and revision. At final revision some patients still had relevant anterior laxity (27 % grade C for Bonin [22, 23], 2 for Zaffagnini [21]).

Radiographically, the midterm (4–5 years) evolution of OA medial femorotibial compartment was stabilized. At 8.5 years, Zaffagnini [21] found only one increase of one case for grade C compared to the preop level (18 versus 17). This inhibitory effect on the evolution OA is sustainable beyond 10 years. Bonin [22, 23] reviewed the patients 11 years later in the same group as Dejour [10] found only five cases of aggravation of class (17 %).

These results should be compared with the isolated ACL grafts with 10 years of follow-up, where the rate of change in OA varies between 15 and 25 % [28, 29]. In case of isolated ACL reconstruction without medial meniscectomy, the increase in the rate of osteoarthritis is 10 % of OA against more than 40 % when a medial meniscectomy pre- or intraoperatively was performed [28] [8]. In all these studies, the percentage of medial meniscectomy was between 60 and 100 %.

A controversial topic regarding HTO is the relevance of posterior tibial slope and its effect on ACL-deficient knee with chronic laxity. Bonin [30] showed the important role played by the genu varum and tibial slope. When the tibial slope exceeds 13°, it is considered excessive, and a deflection osteotomy may be associated with the ACL graft reconstruction [4, 31]. There is a significant correlation between the correction of posterior tibial slope and correction of anterior tibial translation [30] [31, 32]. The slope should be corrected to approximately 4°. The indication must be made in a patient with minimal osteoarthritis, anterior tibial translation difference of more than 10 mm, and a posterior tibial slope of more than 13°.

Conclusion

In some cases, after OA progression in the ACL-deficient knee, the combined procedure with HTO and ACL reconstruction is indicated to restore alignment and knee stability and allow for return to recreational activities and sports. This is a salvage procedure to improve function and pain in order to hopefully avoid a more larger surgical procedure such as knee arthroplasty in young patients.

References

1. Dejour H, Dejour D, Aït Si Selmi T (1996) Laxités chroniques antérieures. Pathologie du genou du sportif in Conférence d'Enseignement SOFCOT, vol 59. Expansion Scientifique Française, Paris, pp 83–93
2. Hulet C, Schiltz D, Locker B, Texier A, Tallier E, Vielpeau C (1999) Le traitement des lésions méniscales dans les laxités antérieures du genou. Ann Orthop Ouest 32:73–80
3. Neyret P, Aït Si Selmi (2002) Instabilités du genou. Encycl Méd Chir Appar Locomoteur 14080 B^{10}: 15
4. Dejour D, Bonin N, Schiavon M, Sanchez S (2003) Arthrose et laxité chronique antérieure. Les facteurs de l'arthrose et les options thérapeutiques. Pathologie ligamentaire du genou. Springer Verlag, Paris, pp 549–565
5. Dejour H, Walch G, Deschamps G, Chambat P (1987) Arthrose du genou sur laxité chronique antérieure. Rev Chir Orthop 73:157–170
6. Beaufils P (2003) Traitement moderne des lésions méniscales. Réparation méniscale – Reconstruction méniscale. Cahiers d'Enseignement SOFCOT, vol 79. Expansion scientifique française, Paris, pp 69–88
7. Lerat JL, Moyen B, Garin C, Mandrino A, Besse JL, Brunet-Guedj E (1993) Laxité antérieure et arthrose interne du genou. Résultats de la reconstruction du ligament croisé antérieur associée à une ostéotomie tibiale. Rev Chir Orthop 79:365–374
8. Beaufils P, Cassard X, Charrois O (2004) Réparation méniscale. Rev Chir Orthop 90(Supp 8):3S49–3S76
9. Pierre A, Hulet C, Schiltz D, Locker B, Vielpeau C (2001) Les lésions méniscales laissées en place lors de la ligamentoplastie du LCA. Etude rétrospective à propos de 86 genoux. Rev Chir Orthop 87: 661–668

10. Dejour H, Neyret P, Boileau P, Donell ST (1994) Anterior cruciate reconstruction combined with valgus tibial osteotomy. Clin Orthop 299:220–228
11. Noyes FR, Barber-Westin SD, Hewett T (2000) High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament deficient knees. Am J Sports Med 28:282–296
12. Dejour H, Walch G, Neyret P, Adeline P (1988) Résultat des laxités antérieures chroniques opérées. A propos de 251 cas revus avec un recul minimum de 3 ans. Rev Chir Orthop 74:622–636
13. Mazières B, Tressol-Verrouil E (1997) Généralités sur l'arthrose. Encycl Méd Chir Appar Locomoteur 14–083 C^{10}: 15
14. Neyret P, Aï Si Selmi T, Gluchuk Pires L, avec la participation de Rongieras SF, Boileau P, Lapra C (1999) Conf d'enseignement. Arthrose et laxité. Annales d'arthroscopie, Sauramps médical 25–46
15. Pierrard G, Hulet C, Jambou S, Acquitter Y, Locker B, Vielpeau C (2002) Résultats de 112 laxités antérieures opérées d'une plastie intra et extra articulaire selon la technique de Mac Instosh. Ann Orthop Ouest 34:149–160
16. Lerat JL, Moyen B, Cladiere F, Besse JL, Abidi H (2000) Knee instability after injury to the anterior cruciate ligament. J Bone Joint Surg (Br) 82:42–48
17. Lerat JL, Chotel F, Besse JL, Moyen B (1998) Les résultats après 10 à 16 ans du traitement de la laxité chronique antérieure du genou par une reconstruction du ligament croisé antérieur avec une greffe de tendon rotulien associée à une plastie extra-articulaire externe. Rev Chir Orthop 84:712–727
18. Neyret P, Donnell ST, Dejour D, Dejour H (1993) Partial meniscectomy and anterior cruciate ligament rupture in soccer players, a study with a minimum 20 years follow-up. Am J Sports Med 21:455–459
19. Dejour H, Dejour D, Ait Si Selmi T (1999) Laxités antérieures chroniques du genou traitées par greffe libre de tendon rotulien avec plastie latérale extra-articulaire. 148 cas revus à plus de 10 ans. Rev Chir Orthop 85:777–789
20. Hulet C, Locker B, Schiltz D, Le Tiec T, Vielpeau C (2001) Arthroscopic medial meniscectomy on stable knees: a 12 year follow-up study. J Bone Joint Surg 83:29–31
21. Zaffagnini S, Bonanzinga T, Grassi A, Marcheggiani Muccioli GM, Musiani C, Raggi F, Iacono F, Vaccari V, Marcacci M (2013) Combined ACL reconstruction and closing-wedge HTO for varus angulated ACL-deficient knees. Knee Surg Sports Traumatol Arthrosc 21(4):934–941
22. Bonin N, Aït Si Selmi T, Neyret P (2004) Ostéotomies et laxité antérieure. Cahiers d'Enseignement SOFCOT, vol 86. Expansion scientifique française, Paris, pp 96–103
23. Bonin N, Aït Si Selmi T, Donell ST, Dejour H, Neyret P (2004) Anterior cruciate reconstruction combined with valgus upper tibial osteotomy: 12 years follow-up. Knee 11:431–434
24. Elser F, Imhoff AB (2007) Combined high tibial osteotomy, anterior cruciate ligament reconstruction, and cartilage transplantation in young athletes. Oper Tech Orthop 17:46–50
25. Lattermann C, Jakob RP (1996) High tibial osteotomy alone or combined with ligament reconstruction in anterior cruciate ligament-deficient knees. Knee Surg Traumatol Arthrosc 4:32–38
26. Noyes FR, Barber SD, Simon R (1993) High tibial osteotomy and ligament reconstruction in varus angulated, anterior cruciate ligament-deficient knee. A two- to seven-year follow-up study. Am J Sports Med 21:2–12
27. Boussaton M, Potel JF (2003) Ostéotomie tibiale de valgisation associée à une ligamentoplastie du ligament croisé antérieur utilisant le tendon rotulien: réflexions et indications. Perspectives en arthroscopie (SFA), vol 3. Springer Verlag, Paris, pp 37–41
28. Hulet C, Burdin G, Locker B, Vielpeau C (2004) Résultats et complications après reconstruction du ligament croisé antérieur. Conférence d'Enseignement SOFCOT. Expansion Scientifique Française, Paris, pp 143–160
29. Hulet C, Acquitter Y, Burdin G, Locker B, Vielpeau C (2003) Positionnement des greffes du LCA. Pathologie ligamentaire du genou. Springer Verlag, Paris, pp 307–320
30. Bonin M, Carret JP, Dimnet J, Dejour H (1996) The weight-bearing knee after anterior cruciate ligament rupture. An in vitro biomechanical study. Knee Surg Sports Traumatol Arthrosc 3:245–251
31. Dejour D, Kuhn A, Dejour H (1998) Ostéotomie tibiale de déflexion et laxité chronique antérieure, à propos de 22 cas. Rev Chir Orthop 84 SII:28–29
32. Neyret P, Zuppi G, Aït Si Selmi T (2000) Tibial deflexion osteotomy. Oper Technol Sports Med 8:61–66
33. Badhe NP, Forster IW (2002) High tibial osteotomy in knee instability: the rationale of treatment and early results. Knee Surg Sports Traumatol Arthrosc 10:38–43
34. Boileau P, Neyret PH (1991) Résultats des ostéotomies tibiales de valgisation associées aux plasties du ligament croisé antérieur dans le traitement des laxités antérieures chroniques évoluées. 7ème Journée du genou. ALRM Edition, Lyon, pp 232–238
35. Boss A, Stutz G, Oursin C, Gächter (1995) Anterior cruciate ligament reconstruction combined with valgus tibial osteotomy (combined procedure). Knee Surg Sports Traumatol Arthrosc 3:187–191
36. Demange MK, Camanho GL, Pécora JR, Gobbi RG, Tirico LE, da Mota E, Albuquerque RF (2011) Simultaneous anterior cruciate ligament reconstruction and computer-assisted open-wedge high tibial osteotomy: a report of eight cases. Knee 18(6): 387–391
37. Garin C, Lerat JL, Moyen B (1989) Laxité chronique antérieure et arthrose. Etude d'une série de 31 cas de ligamentoplastie associée à une ostéotomie de

valgisation tibiale. Journées Lyonnaises de Chirurgie du Genou et de Traumatologie du Sport 99–105

38. Imhoff AB, Linke RD, Agneskirchner J (2004) Korrekturosteotomie bei primary-varus-, double-varus-und triple-varus-knieistabilität mit kreuzband-ersatz. Orthopädie 33:201–207
39. Neuschwander DC, Drez D, Praine RM (1993) Simultaneous high tibial osteotomy and ACL reconstruction for combined genu varum and symptomatic ACL tear. Orthopedics 16(6):679–684
40. O'Neill DF, James SL (1992) Valgus osteotomy with anterior cruciate ligament laxity. Clin Orthop 278:153–159
41. Williams RJ III, Wickiewicz TL, Warren RF (2000) Management of unicompartimental arthritis in the anterior cruciate ligament-deficient knee. Am J Sports Med 28:749–760
42. Cantin O, Magnussen RA, Corbi F, Servien E, Neyret P, Lustig S (2015) The role of high tibial osteotomy in the treatment of knee laxity: a comprehensive review. Knee Surg Sports Traumatol Arthrosc 23(10):3026–3037. doi:10.1007/s00167-015-3752-z, Epub 2015 Aug 21
43. Trojani C, Elhor H, Carles M, Boileau P (2014) Anterior cruciate ligament reconstruction combined with valgus high tibial osteotomy allows return to sports. Orthop Traumatol Surg Res 100(2):209–212. doi:10.1016/j.otsr.2013.11.012, Epub 2014 Feb 12
44. Akamatsu Y, Mitsugi N, Taki N, Takeuchi R, Saito T (2010) Simultaneous anterior cruciate ligament reconstruction and opening wedge high tibial osteotomy: report of four cases. Knee 17(2):114–118. doi:10.1016/j.knee.2009.05.006, Epub 2009 Jun 28
45. Schuster P, Schulz M, Richter J (2016) Combined biplanar high tibial osteotomy, anterior cruciate ligament reconstruction, and abrasion/microfracture in severe medial osteoarthritis of unstable varus knees. Arthroscopy 32(2):283–292. doi:10.1016/j.arthro.2015.07.008, Epub 2015 Sep 15
46. Chu CR, Beynnon BD, Buckwalter JA, Garrett WE Jr, Katz JN, Rodeo SA, Spindler KP, Stanton RA (2011) Closing the gap between bench and bedside research for early arthritis therapies (EARTH): report from the AOSSM/NIH U-13 post-joint injury osteoarthritis conference II. Am J Sports Med 39(7):1569–1578. doi:10.1177/0363546511411654, PubMed PMID: 21730208, PubMed Central PMCID: PMC3182453
47. Lohmander LS, Englund PM, Dahl LL, Roos EM (2007) The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. Am J Sports Med 35(10):1756–1769. doi:10.1177/0363546507307396, Epub 2007/09/010363546507307396 [pii]
48. Lohmander LS, Ostenberg A, Englund M, Roos H (2004) High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50(10):3145–3152. doi:10.1002/art.20589, Epub 2004/10/12
49. Lee HH, Chu CR (2012) Clinical and basic science of cartilage injury and arthritis in the football (soccer) athlete. Cartilage 3(1 Suppl):63S–68S. doi:10.1177/1947603511426882, PubMed PMID: 26069610, PubMed Central PMCID: PMC4297167
50. von Porat A, Roos EM, Roos H (2004) High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis 63(3):269–273, Epub 2004/02/14
51. Chu CR, Beynnon BD, Dragoo JL, Fleisig GS, Hart JM, Khazzam M, Marberry KM, Nelson BJ, Group E (2012) The feasibility of randomized controlled trials for early arthritis therapies (earth) involving acute anterior cruciate ligament tear cohorts. Am J Sports Med 40(11):2648–2652. doi:10.1177/0363546512465409
52. Csintalan RP, Inacio MC, Funahashi TT (2008) Incidence rate of anterior cruciate ligament reconstructions. Permanente J 12(3):17–21, PubMed PMID: 21331205, PubMed Central PMCID: PMC3037119
53. Gianotti SM, Marshall SW, Hume PA, Bunt L (2009) Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. J Sci Med Sport/Sports Med Aust 12(6):622–627. doi:10.1016/j.jsams.2008.07.005
54. Chu CR, Andriacchi TP (2015) Dance between biology, mechanics, and structure: a systems-based approach to developing osteoarthritis prevention strategies. J Orthop Res Off Publ Orthop Res Soc 33(7):939–947. doi:10.1002/jor.22817
55. Hosseini A, Li JS, Gill TJ, Li G (2014) Meniscus injuries alter the kinematics of knees with anterior cruciate ligament deficiency. Orthop J Sports Med 2(8):2325967114547346. doi:10.1177/2325967114547346, PubMed PMID: 26535357, PubMed Central PMCID: PMC4555577
56. Johnson DL, Urban WP Jr, Caborn DN, Vanarthos WJ, Carlson CS (1998) Articular cartilage changes seen with magnetic resonance imaging-detected bone bruises associated with acute anterior cruciate ligament rupture. Am J Sports Med 26(3):409–414
57. Potter HG, Jain SK, Ma Y, Black BR, Fung S, Lyman S (2012) Cartilage injury after acute, isolated anterior cruciate ligament tear: immediate and longitudinal effect with clinical/MRI follow-up. Am J Sports Med 40(2):276–285. doi:10.1177/0363546511423380
58. Frobell RB (2011) Change in cartilage thickness, posttraumatic bone marrow lesions, and joint fluid volumes after acute ACL disruption: a two-year prospective MRI study of sixty-one subjects. J Bone Joint Surg Am 93(12):1096–1103. doi:10.2106/JBJS.J.00929
59. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlen L, Eriksson K (2014) Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. Am J Sports Med 42(5):1049–1057. doi:10.1177/0363546514526139

60. Bear DM, Szczodry M, Kramer S, Coyle CH, Smolinski P, Chu CR (2010) Optical coherence tomography detection of subclinical traumatic cartilage injury. J Orthop Trauma 24(9):577–582. doi:10.1097/BOT.0b013e3181f17a3b, PubMed PMID: 20736798, PubMed Central PMCID: PMC2967018
61. Chu CR, Williams AA, West RV, Qian Y, Fu FH, Do BH, Bruno S (2014) Quantitative magnetic resonance imaging UTE-T2* mapping of cartilage and meniscus healing after anatomic anterior cruciate ligament reconstruction. Am J Sports Med 42(8):1847–1856. doi:10.1177/0363546514532227
62. Chu CR, Millis MB, Olson SA (2014) Osteoarthritis: from palliation to prevention: AOA critical issues. J Bone Joint Surg Am 96(15), e130. doi:10.2106/JBJS.M.01209, PubMed PMID: 25100783, PubMed Central PMCID: PMC4116563
63. Li X, Kuo D, Theologis A, Carballido-Gamio J, Stehling C, Link TM, Ma CB, Majumdar S (2011) Cartilage in anterior cruciate ligament-reconstructed knees: MR imaging T1{rho} and T2 – initial experience with 1-year follow-up. Radiology 258(2):505–514. doi:10.1148/radiol.10101006, PubMed PMID: 21177392, PubMed Central PMCID: PMC3029884
64. Williams A, Qian Y, Golla S, Chu CR (2012) UTE-T2 * mapping detects sub-clinical meniscus injury after anterior cruciate ligament tear. Osteoarthr Cartil/OARS Osteoarthr Res Soc 20(6):486–494. doi:10.1016/j.joca.2012.01.009
65. Williams A, Qian Y, Bear D, Chu CR (2010) Assessing degeneration of human articular cartilage with ultra-short echo time (UTE) T2* mapping. Osteoarthr Cartil/OARS Osteoarthr Res Soc 18(4):539–546, Epub 2010/02/23. doi: S1063-4584(10)00028-2 [pii]10.1016/j.joca.2010.02.001
66. Scanlan SF, Favre J, Andriacchi TP (2013) The relationship between peak knee extension at heel-strike of walking and the location of thickest femoral cartilage in ACL reconstructed and healthy contralateral knees. J Biomech 46(5):849–854. doi:10.1016/j.jbiomech.2012.12.026
67. Shabani B, Bytyqi D, Lustig S, Cheze L, Bytyqi C, Neyret P (2015) Gait knee kinematics after ACL reconstruction: 3D assessment. Int Orthop 39(6):1187–1193. doi:10.1007/s00264-014-2643-0

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Graft Rupture and Failure After ACL Reconstruction

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44.1 Introduction

Although anterior cruciate (ACL) reconstruction is generally regarded as a successful procedure with an overall 81 % rate of return to sport [6], graft rupture and graft failure are not infrequent. In a systematic review, Wright et al. found a pooled graft rupture rate of 5.8 % at a minimum of 5-year follow-up [68]. A similar graft rupture rate of 4.5 % was reported by Webster et al. at a mean 4.8 years follow-up [65]. Reinjury and graft failure are potentially devastating for the patient and it is therefore important to understand the causes and risk factors of both entities.

44.1.1 Terminology

The terms "graft rupture" and "graft failure" are frequently used interchangeably. Graft failure is a somewhat nonspecific term. It may be used to include graft rupture, graft insufficiency that may or may not be symptomatic or failure of the ACL reconstruction to provide the desired level of function. Indeed, there is considerable overlap of each of these scenarios. However, for the purposes of this chapter, graft failure will be used as a generic term to include all three.

Graft rupture will be used to refer to a traumatic rupture of a previously well-functioning ACL graft. Even so, graft rupture may still be contributed to by a poorly performed ACL reconstruction. For instance, a graft that is impinging in the intercondylar notch due to an excessively anterior placement of the femoral tunnel may, in a sense, be "doomed" from the outset and susceptible to disruption under minimal load. Thus, perceived trauma may play only a small role in the failure of such a graft.

On the other hand, early graft failure – for instance, due to poor control of rotatory laxity of the knee as a result of poor tunnel placement – may prevent the patient from returning to a high activity level because of giving way episodes, which may be perceived as traumatic. To complicate things even further, a patient may function satisfactorily despite significant graft laxity

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being present on examination or an MRI demonstrating a graft rupture. This may be particularly so in the setting of osteoarthritic change.

44.1.2 Causes of Failure Versus Risk Factors

It is worth distinguishing between causes of graft failure and risk factors for reinjury. The cause of graft failure may be able to be determined preoperatively, but findings at revision surgery may also help explain the failure. Graft failure is often multifactorial in aetiology, but at times no obvious cause for failure can be identified. Risk factors for reinjury on the other hand are factors that have been shown to have an association with an increased rate of reinjury, without there being any compromise of the ACL graft.

Understanding causes of graft failure helps the surgeon address them at revision surgery. Identification of risk factors, especially those that are potentially modifiable, is important in reducing further reinjury. Identified risk factors may not only result in modification of revision surgery but also influence the fundamental advice given to the patient about return to sport and the criteria that need to be met for progression during rehabilitation.

44.1.3 Classification of Causes of Graft Failure

In broad terms, the causes of failure can be classified as traumatic, technical and patient related. Within each category there are many individual factors that may coexist. In a study of findings at the time of ACL revision surgery by members of the French Arthroscopic Society, technical errors accounted for two-thirds of ACL graft failures, with trauma accounting for most of the rest [59]. The single most common cause of failure was femoral tunnel malposition. Causes of graft failure are discussed in detail later in this chapter.

As mentioned earlier, the role of trauma in graft failure can be difficult to determine. Putting an unstable knee under load may result in giving way, which is perceived by the patient as a traumatic episode, even though the graft may have already failed before this. It is therefore important to establish the level of function that had been achieved prior to the knee giving way.

The term "patient-related factors" encompasses many entities including generalised ligamentous laxity and associated injuries that may compromise the stability of the knee. The latter may include other ligamentous injuries that have not been adequately addressed, meniscal pathology or meniscal resection and perhaps chondral and osteochondral lesions. Other local factors include failure of incorporation and biological failure of the graft.

44.2 Risk Factors for Graft Failure (See Table 44.1)

44.2.1 Graft Type

44.2.1.1 Autograft Versus Allograft

There has been much literature about the risk for graft rupture with autograft compared to allograft use, and a number of systematic reviews with meta-analyses have been published [11, 17, 31, 32]. These reviews have compared patellar tendon autografts with patellar tendon allografts with mixed findings. An early review by Krych et al. [32] reported that allograft patients were five times more likely to rupture their grafts than patients with autografts. However, this difference was not present when irradiated or chemically treated grafts were excluded from the analysis. Subsequent reviews by Carey et al. [11] and Foster et al. [17] did not find significant differences in graft rupture rates between allografts and autografts. A more recent review by Kraeutler et al. [31] which included 3,013 autograft patients and 604 allograft patients reported an overall graft rupture rate of 4.3 % for the autograft group and 12.7 % for the allograft group. This was significantly different and demonstrated a threefold increase in graft rupture rates for allografts compared to autografts.

The above reviews do not, however, stratify for potentially important reinjury factors such as

Table 44.1 Potential risk factors for ACL graft failure

Risk factor	Comment
Graft type	
Autograft vs. allograft	Patellar tendon (PT) allografts probably have a higher failure rate than PT autografts in young patients
Hamstring vs. patellar tendon autograft	Evidence is conflicting. Registry data suggests slightly higher failure rate with hamstring grafts, but most other studies showing no difference
Graft size	Smaller graft diameter has only been shown to be a relatively small risk factor in two studies, with more studies show no effect
Age	Younger age at surgery is a strong risk factor, particularly less than 20 years old. The reasons for this are unclear
Return to sport	A return to cutting and pivoting sports is a risk factor for further injury
Early return to sport	The small amount of data available shows conflicting results
Contact vs. noncontact injury	Initial contact injury associated with higher rates of reinjury, but this may reflect the type of sport played
Biomechanics	Deficits in hip rotational control, excessive valgus, knee flexor deficits and postural control deficits are associated with increased risk of reinjury
Gender	No clear evidence to support an effect of gender
Height and weight	Increased BMI has not been shown to a risk factor for reinjury
Family history	A positive family history has been shown to a risk factor for reinjury, but it is unclear whether this is a genetic or environmental factor
Tibial slope	Although this has not been extensively investigated, studies from one centre show that increased posterior tibial slope is a risk factor for reinjury
Tunnel position	Hard to assess because of changing views of what constitutes ideal tunnel position. A more vertical alignment has been shown to be a risk factor in one centre

age or activity level. A number of studies have suggested that the failure rate of patellar tendon allografts may be greater than patellar tendon autografts in young patients. In patients 18 or younger, Ellis et al. [14] reported a revision rate of 35 % with allografts compared to only 3 % for autografts. Barrett et al. [7] also found a higher failure rate in high activity patients with an allograft compared to low-activity patients. A recently published review by Wasserstein et al. [62] specifically investigated failure rates between allografts and autografts in young active patients. Graft sources included quadrupled hamstring autografts (463 patients), patellar tendon autografts (325 patients) and various allografts (228 patients). The failure rates for hamstring autografts, patellar tendon autografts and allografts were 9.5 %, 9.8 % and 25 %, respectively. The failure rate for allografts was significantly greater than for both autografts in combination and alone. Overall, this review concluded that allografts perform poorly in young active patients.

44.2.1.2 Hamstring Autograft Versus Patellar Tendon Autograft

A number of studies by the same group have consistently shown no significant differences in rates of ACL graft rupture between hamstring and patellar tendon autografts [8, 9, 35, 51, 53]. As the participants in these studies were derived from two consecutive cohorts, the groups were mixed in regard to activity level. However, a large cohort study of 298 competitive athletes also showed no significant difference between graft rupture rates when hamstring and patellar tendon autografts were compared [34]. Recent data from the MOON cohort similarly shows no difference in the rates of revision surgery between hamstring and patellar tendon autografts [27]. These studies are in contrast to two large registry datasets published by Maletis et al. [38] and Persson et al. [50] which reported hamstring grafts to have a significantly higher risk (1.82 times and 2.3 times, respectively) of revision than patellar tendon grafts. As the end point for these datasets is revision surgery, the number of ruptures that occurred but were not addressed surgically is unknown.

A recently published randomised trial by Mohtadi et al. [43] compared patellar tendon and single-bundle and double-bundle hamstring tendon autografts. Significantly less traumatic reinjuries were reported in the patellar tendon group (3 %) compared to the single-bundle (11 %) and double-bundle (10 %) hamstring tendon groups. There were no between group differences for atraumatic graft failure rates. Younger age was also a significant predictor of traumatic reinjuries.

44.2.2 Graft Size

The relationship between graft diameter and subsequent graft failure has received attention after the publication by Magnussen et al. [37] which showed that small hamstring grafts were a predictor of early graft failure. However, the odds ratio (OR) for patients under 20 years undergoing revision compared to older patients (OR = 18.97) was far greater than the odds ratio for patients with smaller grafts requiring revision compared to patients with larger grafts (OR = 2.2). In patients 20 years or older, there was no difference in revision rates between those with a graft diameter greater than 8 mm and those with a graft diameter of 8 mm or less.

Park et al. [46] also showed greater graft rupture rates in patients with a graft size of less than 8 mm in a mostly nonathletic population. However, the association between graft size and rupture rate was not present when a cutoff of 7.5 mm was used instead of 8 mm. Webster et al. [65] found no relationship between graft size and rupture rates using a cutoff of 7 mm for graft diameter which is the same result as other recent studies by Kamien et al. [30] and Bourke et al. [8]. Overall, there is currently insufficient evidence to conclude that graft size is a major risk factor for graft rupture.

44.2.3 Age

There are an increasing number of cohort studies which show graft rupture or failure rates to be markedly higher in younger-aged patients. In one of the earliest and largest cohort studies to demonstrate an association between age and graft rupture, Shelbourne et al. [56] reported that the 5-year ACL rupture rate was 8.7 % for patients under 18 years, 2.6 % for 18–25-year-olds and only 1.1 % for patients older than 25. Similar rupture rates were subsequently found by Kaeding et al. [26] who reported a rate of 8.2 % for patients 10–19 years compared to a 1.8 % rupture rate in patients over 30 years.

More recent cohort studies have shown even larger discrepancies between younger and older patients. Kamien et al. [30] reported a 25 % graft failure rate in patients aged 25 years or younger compared with only 6 % for those over 25. In a cohort of top-level young athletes (NCCA Division 1 Sports), Kamath et al. [28] reported a 17.2 % rupture rate for patients who injured their ACL before entering college compared to a 1.9 % rate for those who injured their ACL whilst in college. Magnussen et al. [37] and Webster et al. [65] found similar rupture rates for patients under 20 years, with rates of 14.3 % and 13.6 %, respectively. This was notably higher than the respective 0.7 % and 2.4 % rates found in the over 20-year-old patient groups. In the longest follow-up to date, Bourke et al. [8] found that 34 % of patients who were 18 years or younger at surgery had sustained a graft rupture by 15 years compared to only 14 % who were older than 18 years. In the same cohort, young males were found to be the most susceptible with a rupture rate of 46 % at 15 years compared to 14 % in males older than 18 years.

ACL registry data has also shown age to be a risk factor for reinjury. Data from the Danish registry reported that patients younger than 20 at the time of primary surgery had a significantly higher risk (adjusted relative risk of 2.58) of revision ACL reconstruction than patients older than 20 [36]. The Norwegian ACL registry [50] similarly showed that age was a significant risk factor for revision with a hazard ratio of 4.0 for revision in the youngest age group (15–19 years) compared to the oldest (>30 years). Multiple studies from the Swedish ACL registry have been published which indicate age as a risk factor for ACL injury [2, 4, 5, 15, 33]. The most recent work [5] shows that adolescent patients (defined as 13–19 years) have the highest rates of early revision (within 2 years) with an overall incidence of 3 % compared to a less than 1 % incidence in the over 30 age group.

Data from the Kaiser Permanente ACL registry has similarly shown higher revision rates in younger patients with 32 % of all revision surgeries performed in patients 21 years of age and younger [40]. Recent data from the MOON cohort [27] has also shown that younger-aged patients have significantly increased odds for revision surgery.

When taking all the above data together, it is clear that a young age is a significant risk factor for ACL graft rupture. The reasons for this are not clear, but one contributing factor may be the participation of young people in sports that put their knees at greater risk of injury. This is explored in the next section.

44.2.4 Return to Sport

Returning to sports that involve cutting and pivoting has been shown to significantly increase the risk of graft rupture in some studies but not others. Webster et al. [65] found that a return to strenuous cutting/pivoting sports led to an almost fourfold increase in the risk of graft rupture. Salmon et al. [53] similarly showed a twofold increase in the risk of graft rupture for patients who returned to either moderate (i.e. tennis, skiing) or strenuous (i.e. football, basketball) activities. On the other hand, studies by Pinczewski et al. [51] and Kamien et al. [30] did not find a relationship between activity level and graft rupture. Park et al. [46] similarly did not find athletic status (athlete vs nonathletes) to be associated with graft rupture nor did Bourke et al. [9] find a relationship between graft rupture and return to pre-injury sport.

The different ways in which activity level has been defined make synthesis of this data challenging. Whilst the above-referenced studies look at the risk of returning to different types or levels of sport, it is relevant to note that returning to sport itself may be one of the most salient factors associated with subsequent graft injury. To illustrate this, Shelbourne et al. [56] noted that in a sample of 1,415 patients, only 6.6 % of ACL reinjuries occurred for reasons other than sport. It is also worth noting that few studies account for athletic exposure. In one that did, Paterno et al. [48] showed that the ACL injury rate was 15 times greater in people with a past ACL history compared to a control group.

Indeed, the high reinjury rates reported in younger patients may be related to a higher rate of returning to pre-injury sport in this age group. Webster et al. [65] reported that 88 % of younger patients (<20 at surgery) returned to strenuous sport following ACL reconstruction, whereas this was the case for only 53 % of patients in the over 20 group. A recent systematic review also reported that younger patients were significantly more likely to return to their pre-injury sport with the patients who had returned being on average 3 years younger than those who had not returned [6].

44.2.4.1 Early Return to Sport

There is little empirical data on whether an early return to sport is a risk factor for graft rupture. Shelbourne et al. [56] reported that over a 5-year period, patients who returned to full activity before 6 months postoperatively did not have a statistically significantly higher incidence of graft injury than patients who returned to full activity after 6 months. Laboute et al. [34] however showed that those who returned to competition within 7 months of surgery had a greater risk of reinjury than those returning later. The rupture rate was 15.3 % for those who returned early compared to 5.2 % for the later return group.

44.2.4.2 Contact vs. Noncontact Injury

Patients who sustain a contact mechanism of injury appear to be more likely to have a subsequent graft rupture than patients who have a noncontact mechanism of injury. Both Salmon et al. [53] and Webster et al. [65] showed threefold increases in the risk for graft rupture for patients whose initial ACL injury was a contact mechanism. These findings may be reflective to the types of sport played; however, the mechanism by which a contact injury worsens prognosis is unclear.

44.2.5 Biomechanics

Abnormal movement strategies when performing sports-related tasks have been identified in patients who have returned to sports after ACL reconstruction and have been suggested as another potential factor that may increase the risk of ACL reinjury [42, 47, 49, 57, 64]. A prospective cohort study by Paterno et al. [49] which examined neuromuscular and biomechanical factors for second ACL injury found four measures of asymmetry that accurately predicted second ACL injury risk. These included deficits in hip rotational control, excessive frontal plane knee mechanics, knee flexor deficits and postural control deficits [24]. This study importantly showed that abnormal movement patterns after ACL reconstruction were not isolated to the injured knee, which has implications for rehabilitation. However, within the context of this chapter, it is relevant to note that the majority of patients (77 %) in this cohort study sustained second injuries to the contralateral knee rather than sustaining a graft rupture.

44.2.6 Gender

Studies which have investigated patient sex as a risk factor for graft rupture have either shown no influence or have shown male patients, particularly younger males, to be at greater risk [8, 9, 25, 34, 35, 37, 46, 51, 53, 55, 56, 65]. Data from both the Danish [36] and Norwegian [50] ACL registries as well a data from the MOON cohort [27] report no effect of sex on the risk for ACL revision surgery. Data from the Swedish ACL registry shows higher rates of revision ACL reconstruction in young females aged 15–18 years compared with males of the same age group [1]. It is therefore reasonable to conclude that to date there is no clear-cut relationship between sex and the risk for graft rupture.

44.2.7 Height and Weight

Although an increased BMI has been shown in one study to be a risk factor for noncontact ACL injuries in females [60], the influence of height and weight has not been extensively investigated. In their study of the influence of age and graft diameter on the risk of ACL graft rupture, Magnussen et al.[37] did not find any association between the ratio of graft diameter to patient weight, height or BMI and the risk of reinjury. Similarly, Park et al. [46] did not find a correlation between graft rupture and patient weight, height or BMI. Analysis of data from the Kaiser Permanente ACL Reconstruction registry also did not demonstrate BMI to be a risk factor for revision ACL reconstruction [39].

44.2.8 Family History

Bourke et al. [9] and Webster et al. [65] both found a significant relationship between a positive family history for ACL injuries and graft rupture. In both studies having a first-degree relative who also sustained an ACL injury doubled the risk for graft rupture. Given the limited number of studies, it is difficult to draw firm conclusions about the influence a positive family history has on graft rupture. It is also difficult to know whether an association represents a true genetic risk or rather an active family lifestyle.

44.2.9 Tibial Slope

Increased posterior slope of the tibial plateau increases anterior tibial translation [20] and has been suggested as a risk factor for primary ACL injury [10]. However, the data is conflicting and has been well summarised in a systematic review [66]. Webb et al. [63] investigated posterior tibial slope of those in ACL-reconstructed patients who had a further ACL injury and found a significant association between increased tibial slope and further ACL injury, particularly in those patients who sustained both an ACL graft rupture and a contralateral ACL rupture. The mean posterior tibial slope in patients who did not sustain a further ACL injury was 8.5°. Patients with a slope of 12° had a five times increased risk of further ACL injury.

44.2.10 Tunnel Position

The influence of bone tunnel position on graft rupture is difficult to analyse as there is no universally agreed method of describing tunnel position and no clear consensus on what constitutes good tunnel position. Indeed, concepts of ideal tunnel position continue to evolve. Nonetheless, there is evidence to indicate that tunnel position is important and some examples will be provided.

In a 15-year follow-up of patients who had undergone hamstring reconstruction for an isolated ACL tear, Bourke et al.[8] found that patients who sustained a graft rupture had a significantly more posteriorly placed tibial tunnel than those who did not, whereas there was no difference in femoral tunnel position or graft inclination angle. The same group also reported [35] an association between graft rupture and nonideal tunnel position – using the previously described criteria – for both patellar tendon and hamstring grafts.

Over the past decade or so, there has been an increased tendency to drill the femoral tunnel via the anteromedial portal in an attempt to achieve a more anatomic positioning of the graft. Although Magnussen et al. [37] did not observe any difference in revision rates based on the technique used to drill the femoral tunnel, data from the Danish Knee Ligament Reconstruction Register [52] has however shown a significantly increased cumulative revision rate after 4 years for ACL reconstructions where the femoral tunnel was drilled via the anteromedial portal (5.2 %) compared to drilling via the tibial tunnel (3.2 %). Whether this reflects uptake of a new technique or greater stress being placed on a more anatomic graft is unclear.

Apart from its impact on clinical outcome and the risk of reinjury, tunnel position is also an important consideration in revision surgery and is further discussed in the following section.

44.3 Causes of Graft Failure

As mentioned earlier, the classification of causes of graft failure is difficult. Precise definitions of the potential causes are often lacking. For instance, a traumatic event is frequently cited as a cause of failure, but there is no consensus as to what constitutes a traumatic event. This is further compounded by the overlapping and multifactorial nature of the factors involved, well demonstrated in the study from the MARS group which reported a combination of causes of graft failure in 37 % of patients undergoing revision ACL reconstruction [22]. Ahn et al. [3] reported an even higher number of patients (59 %) with multiple causes for their graft failure. In addition, different authors may include the same entity in different subgroups, making synthesis of the literature difficult, or include an “unknown cause” category.

Despite these inherent difficulties and limitations, a review of the literature was undertaken to identify the reported findings at revision ACL reconstruction surgery that may explain the causes of graft failure. The results are summarised in Table 44.2, which uses the following principal categories to group the findings: new trauma, technical issues and patient-related factors.

44.3.1 New Trauma

New trauma is stated as a cause of failure for between one-third and two-thirds of patients undergoing revision ACL reconstruction, although only two papers cited it as the cause of failure in more than 50 % of patients [41, 54]. However, it is difficult to determine the actual role of the trauma when other factors are also identified.

Some authors distinguish between early (<6 months) and late failures [29, 54], with the implication being that early failures are mainly due to factors such as fixation failure and biological failure, whereas late failures are more likely to be due to trauma and tunnel malposition. However, because of the inconsistency of reporting of the time from primary surgery to injury, as well as of multiple potential causes of failure, it is difficult to draw any conclusions about this.

44.3.2 Technical Issues

Technical issues that may have contributed to ACL graft failure are typically identified in

Table 44.2 Summary of causes of failure (blank cell indicates no data provided; because multiple causes of failure may coexist, percentages may add up to more than 100)

	New trauma	Technical error							Patient related				
		Tunnel malposition				Fixation failure	Prosthetic graft failure	Not specified	Biological or Unknown	Infection	Instability or hyperlaxity	Tunnel widening	Malalignment
		Femoral	Tibial	Both	Not specified								
Ahn et al. [3]	18 %	34 %	20 %	39 %					16 %		5 %		
Denti et al. [12]	35 %						10 %	42 %	3 %				
Diamantopoulos et al. [13]	24 %			63 %			6 %		2 %		3 %	2 %	
Ferreti et al. [16]	47 %				33 %		13 %		7 %				
Garofalo et al. [18]		79 %											
Grossman et al. [21]	48 %							35 %	17 %				
Lind et al. [36]	38 %	20 %	6 %						24 %	2 %	3 %	2 %	
Mars Group et al. [22]	32 %	49 %	23 %			4 %			7 %		2 %		3 %
Mayr et al. [41]	56 %			32 %									
Salmon et al. [54]	65 %				22 %	2 %			11 %				
Trojani et al. [59]	30 %	36 %	11 %			5 %			15 %	2 %	9 %		
Wright et al. [68]	49 %							46 %	5 %				

one-third of patients undergoing revision ACL reconstruction, although Salmon et al. reported technical issues in only 24 %, but this was a single surgeon series. On the other hand, in a large multicentre study the MARS group identified technical issues in 53 %. Some of the more frequent technical issues are discussed below.

44.3.2.1 Tunnel Malposition

Although a number of papers describe their technique of evaluation of tunnel position on plain radiographs [18, 29, 54, 58, 59], methods and threshold values vary between studies. In addition, significant intra-observer and interobserver variability has been reported [61]. Defining tunnel malposition at the time of surgery is even more subjective, with no reliable criteria having been reported. It should also be recognised that concepts of ideal tunnel position have changed during the two decades in which the relevant studies have been published.

Femoral tunnel malposition is the most frequently identified technical issue. In a small series, Garofalo et al. [18] reported that 79 % of femoral tunnels were too anteriorly positioned. The MARS Group [22] found that 48 % patients undergoing revision ACL reconstruction had malpositioned femoral tunnels, whilst Trojani et al. [59] reported 36 %. In a later report from the MARS Group [44] that focused specifically on femoral tunnel position, femoral tunnel malposition alone accounted for 25 % of failures. When combined with other causes, it accounted for up to 48 %. The most common errors were too vertical (36 %), too anterior (30 %) or both (27 %).

Tibial malposition is less frequent than femoral tunnel malposition and is often reported in combination with femoral tunnel malposition or other causative factors. Isolated tibial tunnel malposition was reported in 20 %, 11 % and 6 % by Ahn et al. [3], the report of a French multicentre study [59] and a report for the Danish register for knee ligament reconstruction [36].

44.3.2.2 Fixation Failure

As with tunnel malposition, fixation failure can be hard to define. Whilst it may be possible to identify complete loss of fixation, identification of fixation failure that allows for minor slippage of the graft within a bone tunnel requires specific research tools such as radiostereometric analysis, which is beyond the scope of the reported studies evaluating causes of failure leading to revision. Nonetheless, fixation failure appears to be an uncommon cause of ACL graft failure with rates of 2 %, 4 % and 5 % being reported by Salmon et al. [54], the MARS group [22] and Trojani et al. [59], respectively.

44.3.3 Patient-Related Factors

44.3.3.1 Biological Failure

The concept of biologic failure remains poorly defined. George et al. [19] included immunological response, over-tensioning and infection under this heading, whilst Harner et al. [23] also included aggressive rehabilitation. Except for infection, there is no direct evidence, particularly at the time of revision surgery, that these are causes of graft failure. Denti et al. [12] defined biological failure as when “the patient did not experience a trauma, and the graft appeared well positioned on imaging and arthroscopy” and reported a rate of 3 %. In their systematic review, Wright et al. [67] reported a similar low rate of 5 % for failure of the primary reconstruction due to a “biological cause”. Interestingly the Danish knee ligament register study shows 24 % incidence of unknown causes but makes no reference to biological failure [36].

Infection can be considered as a cause of failure in its own right or as a subcategory of biological causes. It is infrequently reported as a cause of failure and when reported has a low incidence of 2 % [36, 59].

44.3.3.2 Associated Ligamentous Pathology

Like many other potential causative factors, associated ligamentous pathology is difficult to define and may well exist in combination with other factors. Trojani et al. [59] found untreated laxity in 5 % and generalised ligamentous laxity in 4 % of patients undergoing revision ACL reconstruction. The MARS group reported posteromedial and posterolateral laxity as a causative factor in 2 % of a similar group of patients [22]. In contrast, Noyes et al. reported that 44 % of patients undergoing revision ACL reconstruction with a patellar tendon allograft required additional surgery for associated ligamentous laxity, particularly on the lateral side [45]. However, the overall reporting of associated ligamentous pathology as a cause of ACL graft failure is low [29].

44.3.3.3 Limb Malalignment

Limb alignment can affect stability at the knee. When increased varus or valgus at the knee is present, it may exacerbate the effect of collateral instability. However, limb malalignment is rarely reported as a cause of ACL graft failure [45]. The MARS group identified limb malalignment as a causative factor for failure in only 3 % of patients undergoing revision ACL reconstruction [22].

Conclusion

Graft failure includes graft rupture, graft insufficiency that may or may not be symptomatic and failure of the ACL reconstruction to provide the desired level of function. Graft failure is often multifactorial in aetiology, and there are also identified risk factors for reinjury.

A young age is a significant risk factor for ACL graft rupture. The reasons for this are not clear, but one contributing factor may be a higher rate of returning to pre-injury sport in this age group. Despite anecdotal examples, there is little empirical data on whether an early return to sport is a risk factor for graft rupture.

Whilst allografts have been shown to perform poorly in young active patients, there is no consistent data to suggest a difference in reinjury rates between the two most common autografts, hamstring tendon and patellar tendon. Similarly there is currently insufficient evidence to conclude that graft size is a major risk factor for graft rupture.

There is no clear-cut relationship between gender and the risk of graft rupture and BMI does not appear to be a risk factor for revision ACL reconstruction. However, there is some evidence to indicate that patients with an increased posterior tibial slope have an increased risk of further ACL injury.

Analysis of patients undergoing revision ACL reconstruction has shown that the two most frequently cited causes of graft failure are a further episode of trauma and technical issues. However, there are often a number of potential causes identified in the same patient. Of the technical issues, femoral tunnel malposition is the most frequently identified. Tibial malposition is less frequent than femoral tunnel malposition and is often reported in combination with femoral tunnel malposition. Fixation failure appears to be an uncommon cause of ACL graft failure. Patient-related issues are infrequently cited as a cause of failure, but include so-called biological failure, associated ligamentous pathology and limb malalignment.

Overall, understanding the role that a young age plays in increasing the risk of graft failure and eliminating technical issues, particularly femoral tunnel malposition, appear to be the two most important strategies in reducing the risk of ACL graft failure.

References

1. Ahldén M, Samuelsson K, Sernert N, Forssblad M, Karlsson J, Kartus J (2012) The Swedish National Anterior Cruciate Ligament Register: a report on baseline variables and outcomes of surgery for almost 18,000 patients. Am J Sports Med 40(10):2230–2235
2. Ahldén M, Sernert N, Karlsson J, Kartus J (2012) Outcome of anterior cruciate ligament reconstruction with emphasis on sex-related differences. Scand J Med Sci Sports 22(5):618–626
3. Ahn JH, Lee YS, Ha HC (2008) Comparison of revision surgery with primary anterior cruciate ligament reconstruction and outcome of revision surgery between different graft materials. Am J Sports Med 36(10):1889–1895
4. Andernord D, Björnsson H, Petzold M, Eriksson BI, Forssblad M, Karlsson J, Samuelsson K (2014) Surgical predictors of early revision surgery after anterior cruciate ligament reconstruction: results from the Swedish National Knee Ligament register on 13,102 patients. Am J Sports Med 42(7):1574–1582
5. Andernord D, Desai N, Björnsson H, Ylander M, Karlsson J, Samuelsson K (2015) Patient predictors of early revision surgery after anterior cruciate ligament

reconstruction: a cohort study of 16,930 patients with 2-year follow-up. Am J Sports Med 43(1):121–127
6. Ardern CL, Taylor NF, Feller JA, Webster KE (2014) Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sport Med 48(21):1543–1552
7. Barrett GR, Luber K, Replogle WH, Manley JL (2010) Allograft anterior cruciate ligament reconstruction in the young, active patient: Tegner activity level and failure rate. Arthroscopy 26(12):1593–1601
8. Bourke HE, Gordon DJ, Salmon LJ, Waller A, Linklater J, Pinczewski LA (2012) The outcome at 15 years of endoscopic anterior cruciate ligament reconstruction using hamstring tendon autograft for 'isolated' anterior cruciate ligament rupture. J Bone Joint Surg 94B(5):630–637
9. Bourke HE, Salmon LJ, Waller A, Patterson V, Pinczewski LA (2012) Survival of the anterior cruciate ligament graft and the contralateral ACL at a minimum of 15 years. Am J Sports Med 40(9):1985–1992
10. Brandon ML, Haynes PT, Bonamo JR, Flynn MI, Barrett GR, Sherman MF (2006) The association between posterior-inferior tibial slope and anterior cruciate ligament insufficiency. Arthroscopy 22(8):894–899
11. Carey JL, Dunn WR, Dahm DL, Zeger SL, Spindler KP (2009) A systematic review of anterior cruciate ligament reconstruction with autograft compared with allograft. J Bone Joint Surg 91B(9):2242–2250
12. Denti M, Lo Vetere D, Bait C, Schonhuber H, Melegati G, Volpi P (2008) Revision anterior cruciate ligament reconstruction: causes of failure, surgical technique, and clinical results. Am J Sports Med 36(10):1896–1902
13. Diamantopoulos AP, Lorbach O, Paessler HH (2008) Anterior cruciate ligament revision reconstruction: results in 107 patients. Am J Sports Med 36(5):851–860
14. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR (2012) Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. Arthroscopy 28(12):1819–1825
15. Fältström A, Hägglund M, Magnusson H, Forssblad M, Kvist J (2014) Predictors for additional anterior cruciate ligament reconstruction: data from the Swedish national ACL register. Knee Surg Sports Traumatol Arthrosc. doi:10.1007/s00167-014-3406-6, E-print
16. Ferretti A, Conteduca F, Monaco E, De Carli A, D'Arrigo C (2006) Revision anterior cruciate ligament reconstruction with doubled semitendinosus and gracilis tendons and lateral extra-articular reconstruction. J Bone Joint Surg 88A(11):2373–2379
17. Foster TE, Wolfe BL, Ryan S, Silvestri L, Kaye EK (2010) Does the graft source really matter in the outcome of patients undergoing anterior cruciate ligament reconstruction? An evaluation of autograft versus allograft reconstruction results: a systematic review. Am J Sports Med 38(1):189–199
18. Garofalo R, Djahangiri A, Siegrist O (2006) Revision anterior cruciate ligament reconstruction with quadriceps tendon-patellar bone autograft. Arthroscopy 22(2):205–214
19. George MS, Dunn WR, Spindler KP (2006) Current concepts review: revision anterior cruciate ligament reconstruction. Am J Sports Med 34(12):2026–2037
20. Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD (2004) Effects of increasing tibial slope on the biomechanics of the knee. Am J Sports Med 32(2): 376–382
21. Grossman MG, ElAttrache NS, Shields CL, Glousman RE (2005) Revision anterior cruciate ligament reconstruction: three- to nine-year follow-up. Arthroscopy 21(4):418–423
22. Group M, Wright RW, Huston LJ, Spindler KP, Dunn WR, Haas AK, Allen CR, Cooper DE, DeBerardino TM, Lantz BB, Mann BJ, Stuart MJ (2010) Descriptive epidemiology of the Multicenter ACL Revision Study (MARS) cohort. Am J Sports Med 38(10):1979–1986
23. Harner CD, Giffin JR, Dunteman RC, Annunziata CC, Friedman MJ (2001) Evaluation and treatment of recurrent instability after anterior cruciate ligament reconstruction. Instr Course Lect 50:463–474
24. Hewett TE, Di Stasi SL, Myer GD (2013) Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. Am J Sports Med 41(1):216–224
25. Hui C, Salmon LJ, Kok A, Maeno S, Linklater J, Pinczewski LA (2011) Fifteen-year outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft for "isolated" anterior cruciate ligament tear. Am J Sports Med 39(1):89–98
26. Kaeding CC, Aros B, Pedroza A, Pifel E, Amendola A, Andrish JT, Dunn WR, Marx RG, McCarty EC, Parker RD, Wright RW, Spindler KP (2011) Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health 3(1):73–81
27. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, MOON Consortium, Spindler KP (2015) Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. Am J Sports Med 43(7):1583–1590
28. Kamath GV, Murphy T, Creighton RA, Viradia N, Taft TN, Spang JT (2014) Anterior cruciate ligament injury, return to play, and reinjury in the Elite Collegiate Athlete: analysis of an NCAA Division I cohort. Am J Sports Med 42(7):1638–1643
29. Kamath GV, Redfern JC, Greis PE, Burks RT (2011) Revision anterior cruciate ligament reconstruction. Am J Sports Med 39(1):199–217

30. Kamien PM, Hydrick JM, Replogle WH, Go LT, Barrett GR (2013) Age, graft size, and Tegner activity level as predictors of failure in anterior cruciate ligament reconstruction with hamstring autograft. Am J Sports Med 41(8):1808–1812
31. Kraeutler MJ, Bravman JT, McCarty EC (2013) Bone-patellar tendon-bone autograft versus allograft in outcomes of anterior cruciate ligament reconstruction: a meta-analysis of 5182 patients. Am J Sports Med 41(10):2439–2448
32. Krych AJ, Jackson JD, Hoskin TL, Dahm DL (2008) A meta-analysis of patellar tendon autograft versus patellar tendon allograft in anterior cruciate ligament reconstruction. Arthroscopy 24(3):292–298
33. Kvist J, Kartus J, Karlsson J, Forssblad M (2014) Results from the Swedish national anterior cruciate ligament register. Arthroscopy 30(7):803–810
34. Laboute E, Savalli L, Trouve P, Sabot G, Monnier G, Dubroca B (2010) Analysis of return to competition and repeat rupture for 298 anterior cruciate ligament reconstructions with patellar or hamstring tendon autograft in sportspeople. Ann Phys Rehabil Med 53(10):598–614
35. Leys T, Salmon LJ, Waller A, Linklater J, Pinczewski LA (2012) Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: a prospective study of hamstring and patellar tendon grafts. Am J Sports Med 40(3):595–605
36. Lind M, Menhert F, Pedersen AB (2012) Incidence and outcome after revision anterior cruciate ligament reconstruction. Results from the Danish Registry for knee ligament reconstructions. Am J Sports Med 40(7):1551–1557
37. Magnussen RA, Lawrence JT, West RL, Toth AP, Taylor DC, Garrett WE (2012) Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. Arthroscopy 28(4):526–531
38. Maletis GB, Inacio MCS, Desmond JL, Funahashi TT (2013) Reconstruction of the anterior cruciate ligament. Association of graft choice with increased risk of early revision. Bone Joint J 95B(5):623–628
39. Maletis GB, Inacio MC, Desmond JL, Funahashi TT (2013) Reconstruction of the anterior cruciate ligament: association of graft choice with increased risk of early revision. Bone Joint J 95-B(5):623–628
40. Maletis GB, Inacio MC, Funahashi TT (2015) Risk factors associated with revision and contralateral anterior cruciate ligament reconstructions in the Kaiser Permanente ACLR registry. Am J Sports Med 43(3):641–647
41. Mayr HO, Willkomm D, Stoehr A, Schettle M, Suedkamp NP, Bernstein A, Hube R (2012) Revision of anterior cruciate ligament reconstruction with patellar tendon allograft and autograft: 2- and 5-year results. Arch Orthop Trauma Surg 132(6):867–874
42. Miranda DL, Fadale PD, Hulstyn MJ, Shalvoy RM, Machan JT, Fleming BC (2013) Knee biomechanics during a jump-cut maneuver: effects of sex and ACL surgery. Med Sci Sports Exerc 45(5):942–951
43. Mohtadi N, Chan D, Barber R, Paolucci EO (2016) Reruptures, reinjuries, and revisions at a minimum 2-year follow-up: a randomized clinical trial comparing 3 graft types for ACL reconstruction. Clin J Sport Med 26(2):96–107
44. Morgan JA, Dahm D, Levy B, Stuart MJ, Group MS (2012) Femoral tunnel malposition in ACL revision reconstruction. J Knee Surg 25(5):361–368
45. Noyes FR, Barber-Westin SD, Roberts CS (1994) Use of allografts after failed treatment of rupture of the anterior cruciate ligament. J Bone Joint Surg 76A(7):1019–1031
46. Park SY, Oh H, Park S, Lee JH, Lee SH, Yoon KH (2013) Factors predicting hamstring tendon autograft diameters and resulting failure rates after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21:1111–1118
47. Paterno MV, Ford KR, Myer GD, Heyl R, Hewett TE (2007) Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. Clin J Sport Med 17(4):258–262
48. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE (2012) Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. Clin J Sport Med 22(2):116–121
49. Paterno MV, Schmitt LC, Ford KR, Rauh MJ, Myer GD, Huang B, Hewett TE (2010) Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med 38(10):1968–1978
50. Persson A, Fjeldsgaard K, Gjertsen JE, Kjellsen AB, Engebretsen L, Hole RM, Fevang JM (2014) Increased risk of revision with hamstring tendon grafts compared with patellar tendon grafts after anterior cruciate ligament reconstruction: a study of 12,643 patients from the Norwegian Cruciate Ligament Registry, 2004–2012. Am J Sports Med 42(2):285–291
51. Pinczewski LA, Lyman J, Salmon LJ, Russell V, Roe J, Linklater J (2007) A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft. A controlled prospective trial. Am J Sports Med 35(4):564–574
52. Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC (2013) Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: results from the Danish Knee Ligament Reconstruction Register. Arthroscopy 29(1):98–105
53. Salmon LJ, Russell V, Musgrove T, Pinczewski LA, Refshauge K (2005) Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. Arthroscopy 21(8):948–957
54. Salmon LJ, Pinczewski LA, Russell VJ, Refshauge K (2006) Revision anterior cruciate ligament reconstruction with hamstring tendon autograft: 5- to 9-year follow-up. Am J Sports Med 34(10):1604–1614

55. Shelbourne KD, Davis TJ, Klootwyk TE (1998) The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. A prospective study. Am J Sports Med 26(3): 402–408
56. Shelbourne KD, Gray T, Haro M (2009) Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med 37(2):246–251
57. Stearns KM, Pollard CD (2013) Abnormal frontal plane knee mechanics during sidestep cutting in female soccer athletes after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med 41(4):918–923
58. Thomas NP, Kankate R, Wandless F, Pandit H (2005) Revision anterior cruciate ligament reconstruction using a 2-stage technique with bone grafting of the tibial tunnel. Am J Sports Med 33(11):1701–1709
59. Trojani C, Sbihi A, Djian P, Potel JF, Hulet C, Jouve F, Bussiere C, Ehkirch FP, Burdin G, Dubrana F, Beaufils P, Franceschi JP, Chassaing V, Colombet P, Neyret P (2011) Causes for failure of ACL reconstruction and influence of meniscectomies after revision. Knee Surg Sports Traumatol Arthrosc 19(2): 196–201
60. Uhorchak JM, Scoville CR, Williams GN, Arciero RA, St Pierre P, Taylor DC (2003) Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. Am J Sports Med 31(6):831–842
61. Warme BA, Ramme AJ, Willey MC, Britton CL, Flint JH, Amendola AS, Wolf BR, Group MK (2012) Reliability of early postoperative radiographic assessment of tunnel placement after anterior cruciate ligament reconstruction. Arthroscopy 28(7):942–951
62. Wasserstein D, Sheth U, Cabrera A, Spindler KP (2015) A systematic review of failed anterior cruciate ligament reconstruction with autograft compared with allograft in young patients. Sports Health 7(3): 207–216
63. Webb JM, Salmon LJ, Leclerc E, Pinczewski LA, Roe JP (2013) Posterior tibial slope and further anterior cruciate ligament injuries in the anterior cruciate ligament-reconstructed patient. Am J Sports Med 41(12):2800–2804
64. Webster KE, Feller JA (2012) Tibial rotation in anterior cruciate ligament reconstructed knees during single limb hop and drop landings. Clin Biomech 27(5):475–479
65. Webster KE, Feller JA, Leigh WB, Richmond AK (2014) Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J Sports Med 42(3): 641–647
66. Wordeman SC, Quatman CE, Kaeding CC, Hewett TE (2012) In vivo evidence for tibial plateau slope as a risk factor for anterior cruciate ligament injury: a systematic review and meta-analysis. Am J Sports Med 40(7):1673–1681
67. Wright RW, Gill CS, Chen L, Brophy RH, Matava MJ, Smith MV, Mall NA (2012) Outcome of revision anterior cruciate ligament reconstruction: a systematic review. J Bone Joint Surg 94A(6):531–536
68. Wright RW, Magnussen RA, Dunn WR, Spindler KP (2011) Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. J Bone Joint Surg 93A(12): 1159–1165

Nonoperative Management of ACL Rupture

45

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45.1 Introduction

Anterior cruciate ligament (ACL) reconstruction is common after ACL injury, particularly in young, active individuals [39]. Anterior cruciate ligament (ACL) reconstruction is generally considered standard of practice in the United States for young, active individuals early after ACL injuries generally early after injury [4, 9, 11, 12, 21, 40]. In many other developed countries, active individuals are also counseled to have ACLR before returning to jumping, pivoting, or cutting sports. Athletes are also often informed that ACL reconstruction will decrease static knee joint laxity, minimize further damage to the menisci and articular cartilage, and facilitate their return to preinjury level of sport. While it is clear that knee joint laxity is reduced by ACLR, a differential outcome between those who are managed operatively and nonoperatively is not supported [55]. In the last decade, national and international ACL reconstruction registries and cohorts as well as better tracking overall have resulted in a plethora of information about actual return to play and reinjury numbers after ACL rupture and reconstruction [17, 33, 45, 53, 54, 57]. In addition, there is evidence that athletes are able to return to high-level sports participation without ACL reconstruction and with no difference in clinical, functional, and radiographic outcomes compared to athletes after ACL reconstruction [13, 24–27, 32, 42, 47, 56]. This chapter will discuss the controversies and provide current treatment recommendations for athletes with acute ACL rupture.

45.2 Defining the Problem: Outcomes of ACLR

Consensus among sports orthopedic surgeons and rehabilitation professionals in North America and Europe is that successful outcome after ACL injury and reconstruction is return to sports at the same level and no reinjury [38]. Does this happen? In surveys and reports from their own caseloads in the 1990s and early 2000s, return to sports rates were claimed to be high and reinjury rates low. All of this changed in the mid-2000s with the advent of national and multinational joint registries (notably the Scandinavian knee ligament registries) and the beginning of several multisite

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cohorts (e.g., Multicenter Orthopedic Outcomes Network (MOON)) in the United States and several in Australia [17, 33, 45, 53, 54, 57].

What are the outcomes of ACLR? Not all or even most athletes return to play. In the MOON cohort, 63 % of college and 69 % of high school American football players returned to play football [41]. Forty-three percent of the players were able to return to play at the same self-described performance level. Approximately 27 % felt they did not perform at a level attained before their ACL rupture, and 30 % were unable to return to play at all [41]. Seventy-two percent of soccer players in the MOON cohort returned [10]. Ardern et al. in a 2011 meta-analysis reported 63 % return to preinjury level of sports, with only 44 % to competitive sports, and more recently reported only 55 % return [5, 6]. Shah reported on a 10-year cohort where 61 % (31/49 players) returned to the NFL a mean of 11 months after surgery [52], and 86.1 % returned to play in the NBA after ACL reconstruction in another case series, although playing time, games played, player efficiency ratings, and career lengths were significantly and negatively impacted by the injury/surgery [30]. This reality needs to be contrasted with patient expectations. Feucht et al. studied patient perceptions and found that 94 % of primary ACLR and 84 % of revision ACLR expect to return to the same level of activity with no or only slight restrictions [19]. Clearly, the actual data about outcomes are not getting to the patients.

What about reinjury? A very recent meta-analysis concluded that athletes younger than 18 years who return to sport have a secondary ACL injury rate of 23 % [63]. Both younger age and return to high-level sports activity are independent risk factors for a second ACL injury [61]. These injuries generally occur early in the return-to-play period. The high rate of secondary injury in young athletes who return to sport after ACLR equates to a 30–40 times greater risk of an ACL injury compared with uninjured adolescents [63]. These numbers are not isolated and are remarkably similar around the world. Reinjury rates for soccer in the MOON cohort are 20 % in women, 20–30 % in young athletes in the Hewett prevention cohort, and 17 % in the Shelbourne cohort in those college age and younger [49, 53, 64]. For the Pinczewski cohort in those aged 18 and younger, a further ACL injury occurred in one of three patients over 15 years within the first 5 years after index surgery [8, 45]. A family history of ACL rupture significantly increases the risk for ACL graft ruptures [45]. In addition, osteoarthritis risk is 45–70 % 15 years after ACLR, higher in those who returned to strenuous sports, yet here too, 98 % of patients believe they have no or only slight increased risk of OA [19, 47]. So a significant percentage of athletes do not return to play at the preinjury level after ACLR, and those who do have a high risk of second ACL injury and osteoarthritis development.

45.3 Outcomes of Nonoperative Management

The biggest concern for surgeons is that patients will burn bridges by delaying ACLR. Does surgical delay help, hurt, or make no difference? The existing registries cannot currently shed light on this question. Patients who do not receive surgical treatment for their ACL injury are not included in the registries. Thus, no data on the outcome of nonoperatively treated ACL injuries can be obtained via these registries. Frobell and colleagues' RCT of delayed or no reconstruction versus immediate reconstruction in athletes at 5 years shows that there is no difference in any outcome between those who were operated on straightaway, those who were operated on later, and those who did not have an operation at all [24, 25]. Eitzen et al. and the Delaware-Oslo ACL Cohort demonstrated that a 5-week progressive exercise therapy program in the early stage after ACL injury led to significantly improved knee function before the decision making for reconstructive surgery or further nonoperative management [16, 44]. The compliance to and tolerance for the program was high, with few adverse events.

Quadriceps weakness persists after ACL injury and/or reconstructions and is a strong predictor of outcome [14, 35, 36, 48]. Two methodologically strong studies found no differences in quadriceps strength between operatively and nonoperatively managed patients 2–5 years after ACL injury [2, 3, 18]. Grindem et al. reported at 2-year follow-up that 33 % of athletes who underwent reconstruction had strength deficits greater than 10 % compared to 23 % of athletes managed nonoperatively [25]. ACLR, therefore, is not a prerequisite for restoring muscle function.

Grindem et al. compared IKDC scores between athletes managed nonoperatively or with reconstruction at baseline and 2 years later. There were no significant differences between groups at baseline or at 2-year follow-up [26]. Using the Knee Injury and Osteoarthritis Outcome Score (KOOS), Frobell et al. compared patient-reported outcomes at 5 years after ACL injury and found no significant differences in change score from baseline to 5 years in those managed with early reconstruction versus those managed nonoperatively or with delayed reconstruction [25]. Outcomes after ACL injury, whether managed nonoperatively or with ACLR, have similar patient-reported outcome scores [32, 34]. Similar findings are reported for functional performance measures such as hop tests [15, 43].

45.3.1 Return to Sports

Despite common misconceptions, nonoperatively managed athletes can return to sport without the need for reconstruction. Fitzgerald et al. reported a decision-making schema for returning ACL-deficient athletes to sport to complete a competitive season, without further of meniscal or articular cartilage injury. Grindem et al. compared return to sport in operatively and nonoperatively managed athletes after ACL injury. They found no significant differences between groups in level I sports participation and higher level II sports participation in the nonoperative group in the first year after injury [27]. Case reports and reports in the lay press are rampant [62, 65]. Regardless, therefore, of the evidence, high-level athletes can and do return to full activity without ACLR, at least temporarily [23, 28, 62, 65].

In the only study in which the reduction in sport participation can be related to a control group, Roos et al. reported on elite soccer players 3–7 years after the ACL injury [51]. They found that only 30 % were still active in soccer 3 years after injury compared with 80 % in an uninjured control population. In addition, they showed that, after 7 years, none of the injured elite players were active regardless of the type of treatment [51]. Recent data from US professional athletes after ACLR show a profound effect on career longevity [30, 53]. Regardless of treatment, therefore, previously injured athletes retire at a higher rate than athletes without ACL injuries.

45.3.2 Subsequent Surgery/Reinjury

Sixty-one (51 %) knees, 29 treated with early anterior cruciate ligament reconstruction and 32 treated with initial rehabilitation with the option of a later reconstruction, had meniscus surgery over the 5-year follow-up period of the Frobell study [25]. When they accounted for repeated surgery on the same meniscus, there was a lower frequency of meniscus surgery procedures in patients treated with rehabilitation plus early anterior cruciate ligament reconstruction compared with those treated with initial rehabilitation with the option of having a later reconstruction [25]. Of 59 assigned to rehabilitation plus optional delayed ACL reconstruction, 23 underwent delayed ACL reconstruction; the other 36 underwent rehabilitation alone [24, 25]. Grindem et al. reported their ACLR-treated patients were significantly younger, more likely to participate in level I sports and less likely to participate in level II sports prior to injury than the nonoperatively treated patients [26]. Patients managed with ACLR were more likely to sustain a knee reinjury and to participate in level I sports in the second year of the follow-up period. After 2 years, 20 % had experienced knee reinjury. Overall, the incidence of late reconstruction in the nonoperative group was low [26].

45.3.3 Osteoarthritis

A recent systematic review compared operatively and nonoperatively treated patients at a mean of 14 years after ACL injury and found no significant differences between groups in radiographic osteoarthritis [7]. In the Frobell study, at 5 years, there was no difference in the radiographic development of tibiofemoral osteoarthritis treated with reconstruction, done early or as delayed procedures, and those knees that were treated with rehabilitation alone [25]. Fink found return to sports moderated OA development after ACL injuries managed operatively or nonoperatively. Return to sports may be the most important variable [20]. The prevalence of OA does not seem to depend on whether an ACL reconstruction was performed or not. von Porat et al. reported 78 % OA prevalence in both groups after 14 years, Fink et al. reported 78 %–83 % after 10–13 years, and Neuman et al. in a prospective cohort and Oiestad in her systematic review and Tsoukas and colleagues report overall rates that are similar regardless of management strategy [20, 46, 47, 59, 60]. Thus, there is no evidence to suggest that ligament reconstruction prevents future OA [29, 42].

45.4 Clinical Recommendations

45.4.1 Rehab in the Acute Phase

After acute ACL rupture, early treatment should aggressively resolve all impairments. Treatments to decrease effusion like cold, compression, elevation, and especially active motion are supported. Treatments to restore/preserve passive and active knee extension such as stretching and patellar mobilization are critical to outcome long term [1, 37]. Rehabilitation to increase/maintain quadriceps strength must include progressive resisted exercise in a structured program [1, 37, 58]. Neuromuscular electrical stimulation at high intensity also has strong evidence for effectiveness after ACL rupture [1, 37]. Rehabilitation to restore normal movement patterns/gait should be a component of all early rehab programs. Criteria for completion of the impairment resolution phase that should be achieved are minimal joint effusion, full range of motion, quadriceps contraction including SLR without a lag, and walking without a limp [1].

Just achieving a quiet knee, however, is not sufficient prior to surgery. Virtually across all studies, poor physical performance and residual impairments at the end of rehabilitation predicted worse patient-reported outcomes at 2–5 years regardless of whether patients are managed operatively or nonoperatively [18]. Short-term progressive exercise therapy programs should be incorporated in the early stage after ACL injury, to optimize knee function as a first step in the preparation to return to previous activity (or not) with (or without) surgery [16].

The evidence suggests that a 5-week period of progressive rehabilitation including neuromuscular training as described by Eitzen (which has previously been described in detail, including an appendix presenting the specific exercises, progression, and exercise dosage) results in better outcome [16]. The rehabilitation program consisted of heavy resistance strength training, plyometrics, and neuromuscular exercises and is initiated as soon after injury as impairments are resolved.

Return to activity should also follow a criterion-based progression. All active patients returning to sports after ACL injury, except skiers, should perform a running progression (Table 35.1). The running progression begins as a two-mile (3.2 km) activity with alternating jogging and walking. The ratio of run to walk distance is gradually increased and eventually increases to the patient's preferred total mileage [1].

The rehabilitation specialist should incorporate agility drills; sport-specific activities, such as changing directions, accelerating, and decelerating; and plyometrics to train skills in a rehabilitation program that will transfer to return to competitive play [28]. All patients should pass strenuous return to activity sport (RTS) like those presented in Table 35.2. Once cleared, patients should not directly return to competition. Athletes begin with lower-level sports participation in practice following recommendations of Fitzgerald et al. and gradually build up back to competition with monitoring of pain, effusion, and ROM [22]. We recommend a systematic approach for return to sport participation that accounts for a patient's level of pain and apprehension. Attention to factors such as confidence and motivation for return to sports also needs to be considered [50]. Late rehabilitation should also incorporate exercise and postures for secondary prevention.

45.4.2 Counseling Patients

So what should we be counseling to patients? Not all active patients with ACL injury need ACLR to return to an active lifestyle. Just because you have ACLR doesn't mean you will return to sports at all and most likely not at the same level of performance. Risk of reinjury is high in the near term, higher for those who are younger, for both reinjury of the original knee and also new injury of the contralateral knee [61]. Regardless of surgery, the risk of OA is high in the long term. If you need revision surgery, the risk of OA is higher. When current data are used, there is no economic benefit of early ACLR [31]. Best outcomes are achieved by a comprehensive, criterion-based, rehabilitation program before the decision to undergo ACLR or proceed with nonoperative management.

Conclusions

Nonoperative management of ACL rupture in active individuals is, based on the evidence, an option that merits discussion with patients. The literature identifies few differences in clinical, functional outcome short and long term between people managed with ACLR or nonoperatively after ACL rupture. While conventional wisdom is that those who return to play without a reconstruction will extend their injuries and develop osteoarthritis earlier or more severely than those who undergo reconstruction, the literature is not supportive. Counseling of patients and other stakeholders (e.g., parents and coaches) must include clear explanation of the evidence about outcomes of ACLR and nonoperative management as well as risks of returning to jumping, pivoting, and cutting sports. The best evidence suggests that active individuals with ACL rupture should undergo a protracted period of progressive rehabilitation before the decision for or against early ACLR is made.

References

1. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L (2012) Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sports Phys Ther 42(7):601–614
2. Ageberg E, Pettersson A, Fridén T (2007) 15-year follow-up of neuromuscular function in patients with unilateral nonreconstructed anterior cruciate ligament injury initially treated with rehabilitation and activity modification: a longitudinal prospective study. Am J Sports Med 35(12):2109–2117
3. Ageberg E, Thomeé R, Neeter C, Silbernagel KG, Roos EM (2008) Muscle strength and functional performance in patients with anterior cruciate ligament injury treated with training and surgical reconstruction or training only: a two to five-year follow-up. Arthritis Rheum 59(12):1773–1779
4. Andernord D, Karlsson J, Musahl V, Bhandari M, Fu FH, Samuelsson K (2013) Timing of surgery of the anterior cruciate ligament. Arthroscopy 29(11):1863–1871
5. Ardern CL, Taylor NF, Feller JA, Webster KE (2014) Fifty-five percent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. Br J Sports Med 48(21):1543–1552
6. Ardern CL, Webster KE, Taylor NF, Feller JA (2011) Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. Br J Sports Med 45(7):596–606
7. Barenius B, Ponzer S, Shalabi A, Bujak R, Norlén L, Eriksson K (2014) Increased risk of osteoarthritis after anterior cruciate ligament reconstruction: a 14-year follow-up study of a randomized controlled trial. Am J Sports Med 42(5):1049–1057
8. Bourke HE, Salmon LJ, Waller A, Patterson V, Pinczewski LA (2012) Survival of the anterior cruciate ligament graft and the contralateral ACL at a minimum of 15 years. Am J Sports Med 40(9):1985–1992
9. Bradley JP, Klimkiewicz JJ, Rytel MJ, Powell JW (2002) Anterior cruciate ligament injuries in the National Football League: epidemiology and current treatment trends among team physicians. Arthroscopy 18(5):502–509
10. Brophy RH, Schmitz L, Wright RW, Dunn WR, Parker RD, Andrish JT, McCarty EC, Spindler KP (2012) Return to play and future ACL injury risk after ACL reconstruction in soccer athletes from the Multicenter Orthopedic Outcomes Network (MOON) group. Am J Sports Med 40(11):2517–2522

11. Chalmers PN, Mall NA, Moric M, Sherman SL, Paletta GP, Cole BJ, Bach BR Jr (2014) Does ACL reconstruction alter natural history? A systematic literature review of long-term outcomes. J Bone Joint Surg Am 96(4):292–300
12. Delay BS, Smolinski RJ, Wind WM, Bowman DS (2001) Current practices and opinions in ACL reconstruction and rehabilitation: results of a survey of the American Orthopedic Society for Sports Medicine. Am J Knee Surg 14(2):85–91
13. Eggerding V, Meuffels DE, Bierma-Zeinstra SM, Verhaar JA, Reijman M (2015) Factors related to the need for surgical reconstruction after anterior cruciate ligament rupture: a systematic review of the literature. J Orthop Sports Phys Ther 45(1):37–44
14. Eitzen I, Holm I, Risberg MA (2009) Preoperative quadriceps strength is a significant predictor of knee function two years after anterior cruciate ligament reconstruction. Br J Sports Med 43(5):371–376
15. Eitzen I, Moksnes H, Snyder-Mackler L, Engebretsen L, Risberg MA (2010) Functional tests should be accentuated more in the decision for ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18(11): 1517–1525
16. Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA (2010) A progressive 5-week exercise therapy program leads to significant improvement in knee function early after anterior cruciate ligament injury. J Orthop Sports Phys Ther 40(11):705–721
17. Engebretsen L, Forssblad M (2009) Why knee ligament registries are important…. Knee Surg Sports Traumatol Arthrosc 17(2):115–116
18. Ericsson YB, Roos EM, Frobell RB (2013) Lower extremity performance following ACL rehabilitation in the KANON-trial: impact of reconstruction and predictive value at 2 and5 years. Br J Sports Med 47(15):980–985
19. Feucht MJ, Cotic M, Saier T, Minzlaff P, Plath JE, Imhoff AB, Hinterwimmer S (2016) Patient expectations of primary and revision anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 24(1):201–207
20. Fink C, Hoser C, Hackl W, Navarro RA, Benedetto KP (2001) Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture – is sports activity a determining variable? Int J Sports Med 22(4):304–309
21. Fithian DC, Paxton LW, Goltz DH (2002) Fate of the anterior cruciate ligament-injured knee. Orthop Clin N Am 33(4):621–636
22. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) Proposed practice guidelines for nonoperative anterior cruciate ligament rehabilitation of physically active individuals. J Orthop Sports Phys Ther 30(4):194–203
23. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. Phys Ther 80(2): 128–140
24. Frobell RB, Roos EM, Roos HP, Ranstam J, Lohmander LS (2010) A randomized trial of treatment for acute anterior cruciate ligament tears. N Engl J Med 363(4):331–342
25. Frobell RB, Roos HP, Roos EM, Roemer FW, Ranstam J, Lohmander LS (2013) Treatment for acute anterior cruciate ligament tear: five year outcome of randomised trial. Br Med J 232:1–12
26. Grindem H, Eitzen I, Engebretsen L, Snyder-Mackler L, Risberg MA (2014) Nonsurgical or surgical treatment of ACL injuries: knee function, sports participation, and knee reinjury: the Delaware-Oslo ACL Cohort Study. J Bone Joint Surg Am 96(15): 1233–1241
27. Grindem H, Eitzen I, Moksnes H, Snyder-Mackler L, Risberg MA (2012) A pair-matched comparison of return to pivoting sports at 1 year in anterior cruciate ligament-injured patients after a nonoperative versus an operative treatment course. Am J Sports Med 40(11):2509–2516
28. Hurd WJ, Axe MJ, Snyder-Mackler L (2008) A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with anterior cruciate ligament injury: part 1, outcomes. Am J Sports Med 36(1):40–47
29. Kessler MA, Behrend H, Henz S, Stutz G, Rukavina A, Kuster MS (2008) Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of conservative versus reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 16(5):442–448
30. Kester BS, Behery OA, Minhas SV, Hsu WK (2016) Athletic performance and career longevity following anterior cruciate ligament reconstruction in the National Basketball Association. Knee Surg Sports Traumatol Arthrosc [Epub ahead of print]
31. Kiadaliri AA, Englund M, Lohmander LS, Steen Carlsson K, Frobell RB (2016) No economic benefit of early knee reconstruction over optional delayed reconstruction for ACL tears: registry enriched randomised controlled trial data. Br J Sports Med 50(9):558–563
32. Kostogiannis I, Ageberg E, Neuman P, Dahlberg L, Friden T, Roos H (2007) Activity level and subjective knee function 15 years after anterior cruciate ligament injury: a prospective, longitudinal study of nonreconstructed patients. Am J Sports Med 35(7):1135–1143
33. Leys T, Salmon L, Waller A, Linklater J, Pinczewski L (2012) Clinical results and risk factors for reinjury 15 years after anterior cruciate ligament reconstruction: a prospective study of hamstring and patellar tendon grafts. Am J Sports Med 40(3):595–605
34. Linko E, Harilainen A, Malmivaara A, Seitsalo S (2005) Surgical versus conservative interventions for anterior cruciate ligament ruptures in adults. Cochrane Database Syst Rev 18(2):CD001356
35. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L (2013) Pre-operative quadriceps strength predicts IKDC2000 scores 6 months after anterior cruciate ligament reconstruction. Knee 20(3):208–212
36. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L (2013) Symmetry restoration and functional recovery

before and after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21(4):859–868

37. Logerstedt DS, Snyder-Mackler L, Ritter RC, Axe MJ, Godges JJ (2015) Knee stability and movement coordination impairments: knee ligament sprain. J Orthop Sports Phys Ther 40(4):A1–A37
38. Lynch AD, Logerstedt DS, Grindem H, Eitzen I, Hicks GE, Axe MJ, Engebretsen L, Risberg MA, Snyder-Mackler L (2015) Consensus criteria for defining "successful outcome" after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. Br J Sports Med 49(5):335–342
39. Mall NA, Chalmers PN, Moric M, Tanaka MJ, Cole BJ, Bach BR Jr, Paletta GA Jr (2014) Incidence and trends of anterior cruciate ligament reconstruction in the United States. Am J Sports Med 42(10):2363–2370
40. Marx RG, Jones EC, Angel M, Wickiewicz TL, Warren RF (2003) Beliefs and attitudes of members of the American Academy of orthopaedic surgeons regarding the treatment of anterior cruciate ligament injury. Arthrosc J Arthrosc Relat Surg 19(7):762–770
41. McCullough KA, Phelps KD, Spindler KP (2012) Return to high school- and college-level football after anterior cruciate ligament reconstruction: a Multicenter Orthopaedic Outcomes Network (MOON) cohort study. Am J Sports Med 40(11): 2523–2529
42. Mihelic R, Jurdana H, Jotanovic Z, Madjarevic T, Tudor A (2011) Long-term results of anterior cruciate ligament reconstruction: a comparison with non-operative treatment with a follow-up of 17-20 years. Int Orthop 35(7):1093–1097
43. Moksnes H, Risberg MA (2009) Performance-based functional evaluation of non-operative and operative treatment after anterior cruciate ligament injury. Scand J Med Sci Sports 19(3):345–355
44. Moksnes H, Snyder-Mackler L, Risberg MA (2008) Individuals with an anterior cruciate ligament-deficient knee classified as noncopers may be candidates for nonsurgical rehabilitation. J Orthop Sports Phys Ther 38(10):586–595
45. Morgan MD, Salmon LJ, Waller A, Roe JP, Pinczewski LA (2016) Fifteen-year survival of endoscopic anterior cruciate ligament reconstruction in patients aged 18 years and younger. Am J Sports Med 44(2):384–392
46. Neuman P, Englund M, Kostogiannis I, Friden T, Roos H, Dahlberg LE (2008) Prevalence of tibiofemoral osteoarthritis 15 years after nonoperative treatment of anterior cruciate ligament injury: a prospective cohort study. Am J Sports Med 36(9): 1717–1725
47. Oiestad BE, Engebretsen L, Storheim K, Risberg MA (2009) Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. Am J Sports Med 37(7):1434–1443
48. Otzel DM, Chow JW, Tillman MD (2015) Long-term deficits in quadriceps strength and activation following anterior cruciate ligament reconstruction. Phys Ther Sport Phys Ther Sport 16(1):22–28
49. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE (2014) Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. Am J Sports Med 42(7): 1567–1573
50. Roessler K, Andersen TE, Lohmander S, Roos EM (2015) Motives for sports participation as predictions of self-reported outcomes after anterior cruciate ligament injury of the knee. Scand J Med Sci Sports 25(3):435–440
51. Roos H, Ornell M, Gardsell P et al (1995) Soccer after anterior cruciate ligament injury: an incompatible combination? A national survey of incidence and risk factors and a 7-year follow-up of 310 players. Acta Orthop Scand 66:107–112
52. Shah VM, Andrews JR, Fleisig GS, McMichael CS, Lemak LJ (2010) Return to play after anterior cruciate ligament reconstruction in National Football League athletes. Am J Sports Med 38(11): 2233–2239
53. Shelbourne KD, Gray T, Haro M (2009) Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med 37(2):246–251
54. Shelbourne KD, Sullivan AN, Bohard K, Gray T, Urch SE (2009) Return to basketball and soccer after anterior cruciate ligament reconstruction in competitive school-aged athletes. Sports Health 1(3):236–241
55. Smith TO, Davies L, Hing CB (2010) Early versus delayed surgery for anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Knee Surg Sports Traumatol Arthrosc 18(3):304–311
56. Smith TO, Postle K, Penny F, McNamara I, Mann CJV (2014) Is reconstruction the best management strategy for anterior cruciate ligament rupture? A systematic review and meta-analysis comparing anterior cruciate ligament reconstruction versus non-operative treatment. Knee 21(2):462–470
57. Spindler KP, Huston LJ, Wright RW et al (2011) The prognosis and predictors of sports function and activity at minimum 6 years after anterior cruciate ligament reconstruction a population cohort study. Am J Sports Med 39(2):348–359
58. Tsepis E, Vagenas G, Ristanis S, Georgoulis AD (2006) Thigh muscle weakness in ACL-deficient knees persists without structured rehabilitation. Clin Orthop Relat Res 450(450):211–218
59. Tsoukas D, Fotopoulos V, Basdekis G, Makridis KG (2016) No difference in osteoarthritis after surgical and non-surgical treatment of ACL-injured knees after 10 years. Knee Surg Sports Traumatol Arthrosc 24(9):2953–2959
60. von Porat A, Roos EM, Roos H (2004) High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis 63(3):269–273

61. Webster KE, Feller JA, Leigh WB, Richmond AK (2014) Younger patients are at increased risk for graft rupture and contralateral injury after anterior cruciate ligament reconstruction. Am J Sports Med 42(3):641–647
62. Weiler R, Monte-Colombo M, Mitchell A, Haddad F (2015) Non-operative management of a complete anterior cruciate ligament injury in an English Premier League football player with return to play in less than 8 weeks: applying common sense in the absence of evidence. BMJ Case Rep. doi:10.1136/bcr,2014-208012
63. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD (2016) Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. Am J Sports Med 44(7):1861–1876
64. Wright RW, Dunn WR, Amendola A, Andrish JT, Bergfeld J, Kaeding CC, Marx RG, McCarty EC, Parker RD, Wolcott M, Wolf BR, Spindler KP (2007) Risk of tearing the intact anterior cruciate ligament in the contralateral knee and rupturing the anterior cruciate ligament graft during the first 2 years after anterior cruciate ligament reconstruction: a prospective MOON cohort study. Am J Sports Med 35(7):1131–1134
65. http://xgames.espn.go.com/xgames/skiing/article/10399116/some-freeskiers-compete-sochi-knee--injuries. Accessed 19 Mar 2016

Osteotomies in the ACL-Deficient Knee

46

Alberto Grassi, Ronald van Heerwaarden,
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46.1 Introduction

Anterior cruciate ligament (ACL) reconstruction is widely accepted as the standard of treatment for ACL injury, but excellent results are not universal. Failure or poor outcomes have been reported to occur in around 6.2–11.9 % of cases [14]. Numerous factors have been well described as to the etiology of recurrent instability including osseous joint deformity or limb malalignment. In these specific conditions, additional procedures such as osteotomies may be of value in addressing the bony deformity.

Historically, osteotomies have been used for localized medial and lateral compartment gonarthrosis with varus and valgus malalignment, due to their ability to redistribute the mechanical force across the joint. The classical indications for high tibial osteotomy (HTO) [13] included stable knees with no subluxation or thrust, good range of motion (ROM) of at least 15–100°, localized medial compartment OA, minimal or no patellofemoral symptoms, and age younger than 65 years. However, over the last several years, the indications for HTO have expanded to include cases of concomitant varus malalignment with ACL insufficiency [19]. More recently, because of the role of posterior tibial slope in ACL failure [10, 53], HTO correcting the sagittal plane was proven to be of value in certain cases as an option to address recurrent ACLR failure [18, 49].

46.2 ACL Injury and Bone Geometry

Normal anatomic lower limb alignment on the coronal plane is somewhat variable but falls within 5° and 7° of valgus [25]. Similarly, also the posterior tibial slope presents a wide range of values mostly due to different radiographic techniques and is estimated to range between 6 and 11° on the medial compartment and between 9 and 11° in the lateral compartment [32, 57]. These parameters have been demonstrated to play an important role in ACL injury and failure of ACL reconstruction.

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46.3 Varus Malalignment

Combined varus malalignment and ACL laxity represent a complex scenario from a biomechanical and biological point of view. ACL injury has been shown to correlate with development of knee osteoarthritis, especially in the medial compartment leading to a secondary degenerative varus deformity. Ajuied et al. [2] demonstrated a fivefold risk to develop severe knee OA after ACL injury compared to the contralateral healthy knee. In addition, there is an increased risk of medial meniscus injury in unstable knees, thus aggravating the progression of degenerative changes [19, 50] and deformity.

ACL reconstruction, despite good early clinical and functional results, has been unable to completely avoid or delay degenerative changes of the knee joint. Claes and colleagues [12] reported a long-term incidence of knee OA in around 30 % of patients undergoing ACL reconstruction, especially those with concomitant meniscal injury. The scenario is even worse after revision ACL reconstruction, where signs of advanced knee OA were reported in more than 60 % of the cases with involvement of the medial compartment in around 45 % of the cases [22]. Unicompartmental early or advanced medial OA, resulting in varus deformity, represents therefore a common situation in both chronic ACL insufficiency and postoperative ACL reconstruction (Figs. 46.1 and 46.2).

On the other hand, in the case of ACL deficiency and underlying varus morphotype, with the loss of neuromuscular control, the knee is more likely to progress into increased varus and overload the medial compartment. The varus knee with radiographic separation of the lateral tibiofemoral compartment and increased external rotation and hyperextension with an abnormal varus recurvatum position is referred to as a triple-varus knee [8, 40]. The medial compartment tends to have a posterior medial tibial plateau wear pattern in triple-varus knees due to the chronic anterior subluxation of the tibia with respect to the femur [7] (Fig. 46.3).

Finally, an underlying varus morphotype could itself represent a biomechanically unfavorable condition for ACL function, as it has been reported in vitro that [52] varus malalignment produces higher forces on the ACL or ACL graft, especially for higher varus degree associated with varus thrust. This could explain the presentation of both chronic ACL insufficiency in the varus knee, and the tendency of ACL to fail if coexisting varus alignment is not addressed [42].

Fig. 46.1 Long-leg standing radiography of a 21-year-old female with a previous failed ACL reconstruction and medial meniscectomy at the right knee. It is possible to note the varus alignment compared to the contralateral healthy side

In summary, one could conclude that isolated ACL reconstruction may not be sufficient to break the vicious circle of anteroposterior instability, varus deformity, and medial osteoarthritis and that an osseous procedure to redistribute the forces across may be of value.

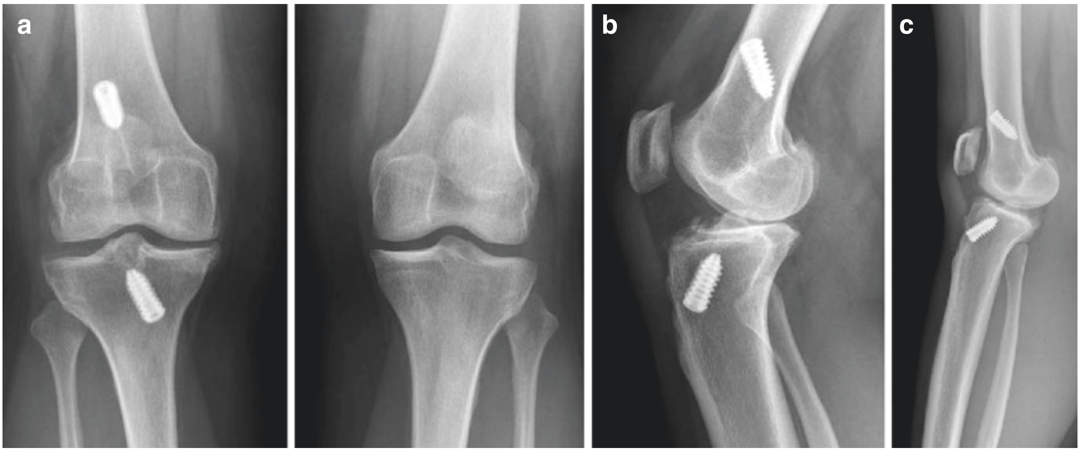

Fig. 46.2 Anteroposterior and lateral radiographs of a 21-year-old female with a previous failed ACL reconstruction and medial meniscectomy at the right knee. Anteroposterior bilateral view (**a**) shows medial joint line narrowing and initial formation of osteophytes. Lateral view (**b**) shows anterior subluxation of the tibia, with posteromedial wearing. The hyperextension (**c**) represents a contraindication to a deflection osteotomy to reduce the posterior tibial slope

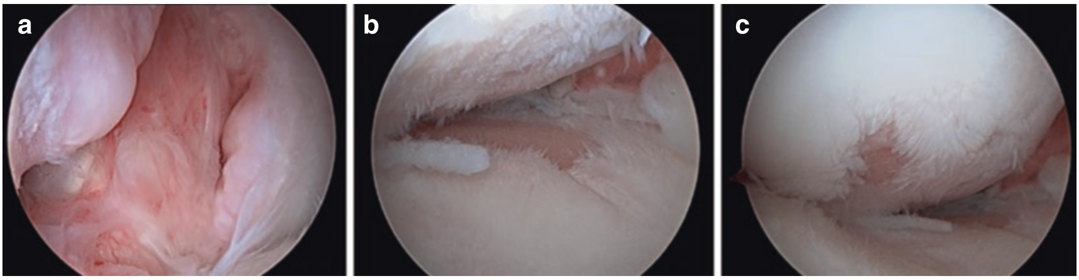

Fig. 46.3 Arthroscopic presentation of a 21-year-old female with a previous failed ACL reconstruction and medial meniscectomy at the right knee. Chronic ACL deficiency is conformed by the ligament absence within the notch that appears narrowed by the presence of osteophytes (**a**). Posteromedial wear of the tibial plateau (**b**) and damage of the corresponding femoral condyle (**c**) are common findings in these patients

46.4 Sagittal Plane Deformity: Posterior Tibial Slope

Although its role was elucidated several years ago, the posterior tibial slope and its relationship to ACL injury and instability have become increasingly recognized in importance more recently. A steep posterior tibial slope, especially in the lateral side, is an accepted risk factor for noncontact ACL injury, both in males, females, and pediatric and adolescent populations [15, 23, 48, 55]. Despite a cutoff value for “at-risk” conditions has not been universally established also due to the different measurement methods, a value >12° is generally considered pathological [24]. Recently, the role of posterior slope has been questioned by Blanke et al. [5]. They reported no significant differences in bony anatomical features of nontraumatic ACL-injured patients compared to a control population. However, the latter study was performed on recreational alpine skiers, thus representing a select subpopulation which may exhibit injury mechanisms that are different from the general population.

The biomechanical background of the correlation between slope and ACL injury relies on the evidence that on the posterior tibial slope, an impulsive compression force (i.e., increased vertical ground-reaction force) during landing generates an anterior shear force [21]. Therefore, a greater posterior tibial slope increases this anterior tibial shear force [37], anterior tibial acceleration and translation, and ACL strain during jump landing activities [28, 35]. Moreover, Dejour and Bonin [16, [34]] in a clinical series demonstrated that increased anterior tibial translation on monopodal stance views correlated with increased posterior tibial slope in patients with intact ACL as well as in those with chronic anterior laxity. Slope has been proposed to play a role also in rotational laxity, as Song et al. [47] correlated a high pivot-shift grade in ACL-deficient patients with the time from injury, anterolateral capsule disruption, lateral meniscus lesion, and also with lateral posterior slope >10.6° measured on MRI according to Hudek et al. [26]. A rotational laxity is also found in patients diagnosed with a so-called bony pivot shift [47] caused by a malunited lateral tibial plateau fracture. The increased slope in the depressed lateral plateau causes symptoms of ACL deficiency in the presence of an intact ACL (Fig. 46.4 bony pivot shift).

The unfavorable effect of an increased posterior tibial slope has been shown to be a risk factor also for revision ACL reconstruction [10, 53]. Webb et al. [53] followed prospectively 181 patients after ACL reconstruction, reporting a significant difference between the radiographically measured medial tibial slope of patients with intact ACL graft (8.5°) and those with both reinjury and contralateral injury (12.9°). The authors quantified the risk of further ACL injury as fivefold compared to patients with medial tibial slope <12°, as this event was reported in 59 % of patients with a value >12°. Similarly, Christensen et al. [10] analyzed the MRI features of 35 patients with successful ACL reconstruction and 35 patients with early graft failure. They reported a higher lateral slope in patients with failed reconstruction (8.4°) compared to intact graft (6.5°) and estimated an odd ratio for graft failure of 1.6, 2.4, and 3.8 for a lateral slope increase of 2°, 4°, and 6°, respectively (Fig. 46.5, failed ACLR).

Thus, in case of failed ACL reconstruction with a posterior tibial slope >10–13° and no evidence of technical errors of the previous reconstructions, a corrective osteotomy could be considered as an option to restore a correct knee biomechanics and avoid further failures.

46.5 Indications and Evaluation for Osteotomy

There are various scenarios of ACL insufficiency that could benefit from a corrective osteotomy, with or without combined ACL reconstruction:

1. Chronic anterior laxity with varus malalignment and unicompartmental medial OA
2. Chronic anterior laxity with varus malalignment and thrust
3. Failed ACL reconstruction with posterior tibial slope >10–13± varus deformity

46.6 Patient Evaluation

Patient selection is one of the most important factors that determine outcome from surgery. The surgeon must determine whether he or she is suffering from underlying instability or if the complaints are caused by degenerative joint disease. The surgeon can differentiate between the two by determining which activities cause symptoms. It is important to distinguish whether the patient is complaining of pain with aggressive activities and pivoting types of movement, indicating instability, or of pain with activities of daily living, indicating arthrosis.

If the patient is diagnosed with chronic ACL deficiency with early medial compartment arthritis and varus malalignment with overload, the physician should optimize conservative care, including unloader bracing, physical therapy, and activity modification. Patients who are experiencing arthritis-type symptoms related to previous meniscectomy, mechanical axis deviation into the medial compartment, and early medial compartment degenerative changes may benefit from a medial or lateral HTO to correct the varus malalignment and unload the medial compartment. The painful symptoms from degenerative joint disease secondary to underlying instability and previous injury are termed *pseudoinstability*. In the setting of previously failed soft tissue reconstruction, one must consider malalignment as a contributing factor.

Fig. 46.4 Bony pivot shift. Left knee of a 38-year-old patient presenting with knee instability after a lateral tibial plateau fracture malunited with posterolateral depression (**a**, **b**), intact cruciate ligaments (**c**), meniscus and cartilage (**d**), and severe downslope of posterolateral plateau (**e**)

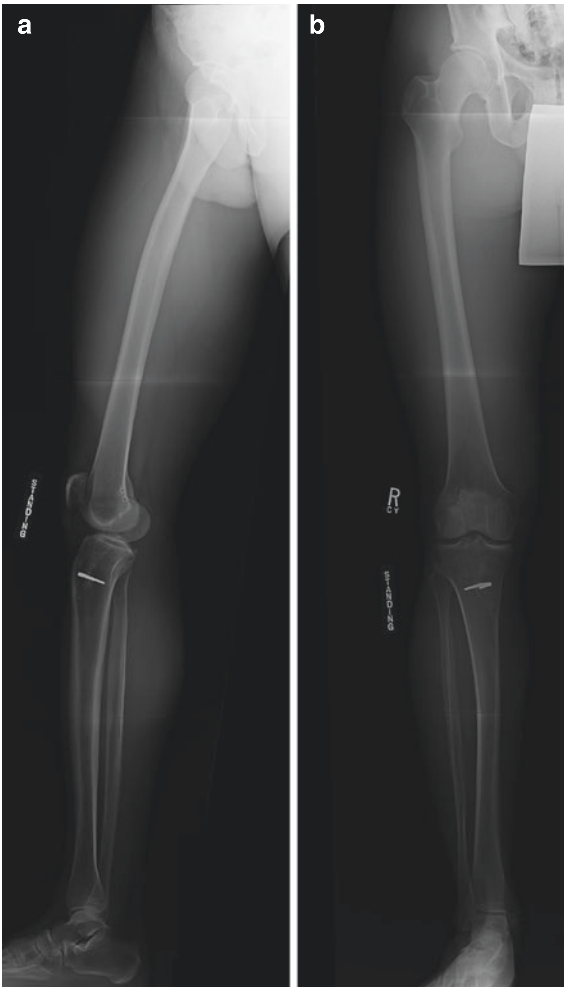

Fig. 46.5 Long-leg anteroposterior (**a**) and lateral (**b**) radiographs of a 35-year-old male patient with two previous failed ACL reconstruction. The coronal alignment appears neutral, while an increased posterior tibial slope is present

In the setting of a younger patient who is experiencing symptoms of instability with underlying malalignment and other meniscal or chondral pathology, the surgeon could consider ACL reconstruction in addition to an osteotomy. Surgeons are currently pushing the envelope for ACL reconstruction in older yet active patients with complaints of instability.

To determine whether an ACL reconstruction is indicated in addition to HTO, the physician must consider the patient's complaints at the time of initial presentation. If an older or less active patient is suffering from mechanical overload and pain, they will likely respond to the osteotomy alone. It is important to assess the entire clinical picture and differentiate pseudoinstability from true instability. If the patient continues to complain of instability after HTO, ACL reconstruction can be considered as a secondary procedure. However, ACL reconstruction alone in the face of malalignment is doomed for continuing symptoms of compartment overload and early failure of the ACL surgery.

Opening- or closing-wedge osteotomy can be performed in the varus knee with an alteration or decrease in slope. The senior authors utilize an OWO to correct varus, but can also decrease slope if required in the ACL-deficient knee. Finally, an anterior closing-wedge osteotomy to decrease the posterior tibial slope has been successfully suggested for the treatment of failed ACL reconstruction, with normal coronal alignment but posterior tibial slope >12–13° [18, 49]. Therefore, this option should be always considered in patients that sustain multiple ACL injuries, usually undergoing several unsuccessful ACL reconstructions that do not present evidence of technical errors, concomitant ligamentous laxities, or coronal malalignment. However, as knee instability represents the major complaint of these patients, the osteotomy should be combined with ACL reconstruction. Not much evidence exists to accurately assess these situations other than surgeon experience.

46.7 Surgical Techniques

Since this is not a surgical technique-focused chapter but rather an evidence-based review, we will discuss preoperative planning and briefly the surgical technique principles involved. A more detailed description of the techniques can be found in other publications [6, 8, 49].

An accurate preoperative planning is mandatory in order to achieve the adequate correction, both on sagittal and coronal plane. Radiographic evaluation begins with assessment of the extent of knee arthrosis and lower extremity alignment with bilateral standard weight-bearing long-leg (hip to ankle) anteroposterior views, standard anteroposterior views in full extension, bilateral weight-bearing posteroanterior tunnel views in 30° of flexion, and lateral and Merchant patellar views (figure X-rays). MRI evaluation is helpful for preoperative planning, as it provides additional information that is often useful in determining soft tissue repair and reconstruction in addition to the osteotomy, such as chondral, meniscal, and soft tissue injury.

46.8 Opening-Wedge High Tibial Osteotomy and ACL Reconstruction

We prefer the medial opening-wedge osteotomy to the lateral closing-wedge osteotomy because, in our experience, precise correction is more likely and overcorrection is less likely. Although this approach increases the stability of a malaligned knee, it also avoids osteotomy of the proximal fibula, thereby avoiding potential instability through the tibiofibular joint and posterolateral corner structures and injury to the peroneal nerve [11, 30, 51]. Amendola and colleagues [2] have shown that by avoiding osteotomy of the proximal fibula, as with a lateral closing-wedge technique, the tibial slope will be forced to decrease because of hinging at the proximal tibiofibular joint.

The amount of axial correction is measured according to Dugdale et al. to avoid overcorrection [20]. The aim of correction may differ dependent of the underlying pathology. In ACL-deficient patients with varus malalignment and thrust, the correction may be aimed at a neutral leg alignment, whereas in patients with varus malalignment and unicompartmental medial OA, the aim is often to correct into valgus leg alignment to unload the damaged medial part of the joint. In the latter group of patients, we plan the osteotomy so that it will place the weight-bearing line—as measured from the center of the femoral head to the center of the tibiotalar joint to pass just lateral to the lateral tibial spine (or 62 % of the width of the tibial joint surface referenced from the medial side). In active patients who hope to return to a high activity level, the goal of correction may be a weight-bearing passing through the center of the knee joint at 50–55 %, even in the presence of medial cartilage damage, because an overcorrected leg would interfere negatively with their athletic abilities. In the setting of an arthritic knee with ACL insufficiency, the additional goal of the osteotomy is to achieve the desired posterior tibial slope in the sagittal plane to enhance stability of the knee [1, 17, 21, 44]. The surgeon must exercise caution in the setting of severe deformity, because the accuracy of correction may be more difficult to determine. Patients with osteoporosis present challenges in obtaining suitable fixation and can require prolonged periods for healing. Other considerations must be given to risk factors for failure, including smokers, prolonged dependency of corticosteroids, immunosuppressants, and chronic illness.

The senior authors do not perform any extensive articular cartilage resurfacing procedures such as autologous chondrocyte implantation (ACI) or meniscal transplantation at the time of this surgery. If they are required, surgery is usually staged; the osteotomy is performed first, followed by soft tissue reconstruction once the patient has recovered from the osteotomy.

As regards accuracy of correction, the wedge base length resulting from preoperative planning is intraoperatively measured and verified [8]. Intraoperative femorotibial alignment can also be verified by fluoroscopy, and an extramedullary alignment rod is used to ensure that the weight-bearing axis is passing through the center of the knee joint. Sabharwal and Zhao [45] have recently cautioned that for obese patients or those with substantial malalignment, supine fluoroscopy alignment measurements without loading of the knee joint do not reflect the axis as accurately as preoperative standing films. In such cases, we believe careful scrutinizing of the preoperative weight-bearing films and the intraoperative fluoroscopic images can still lead to favorable results.

The posterior tibial slope is also assessed intraoperatively and can be changed in opening-wedge valgization HTO by distracting the osteotomy more anteriorly or posteriorly if the patient has any symptomatic cruciate deficiency or excessive anteroposterior translation preoperatively. To allow for this correction in two planes, the hinge point must be cut and afterward compressed or separately fixed (Fig. 46.6 valgus-extension HTO). However, significant corrections of a highly pathological posterior slope cannot be obtained with this technique, and therefore if the major deformity to be corrected is in the sagittal plane, an anterior closing-wedge osteotomy should be preferred. When the desired opening has been achieved, the osteotomy is secured with a plate and, depended on personal preference the gap can be filled with bone graft.

In combined HTO and ACL reconstruction, an arthroscopy and preparation of the notch and femoral tunnel are performed prior to the osteotomy. The osteotomy is performed prior to drilling the tibial tunnel for ACL reconstruction to prevent the creation of a possible stress riser through the ACL tunnel. Arthroscopically assisted ACL reconstruction is done using standard technique with the following considerations. We drill the tibial tunnel anterior and superior to the osteotomy site. The ACL graft is passed through the tibial tunnel and out the femoral tunnel. The senior author's preferences are to use extracortical button fixation. A tibial side interference screw can be placed for primary fixation proximal to the osteotomy site. Secondary fixation can be placed below the osteotomy site, if desired. Bone grafting of the osteotomy site is performed to accelerate bone healing.

Following surgery, the patient is allowed toe-touch weight-bearing with ROM performed within a 0–90° arc for 6 weeks. It is important to begin early postoperative range of motion to prevent stiffness in the knee joint. Radiographs are

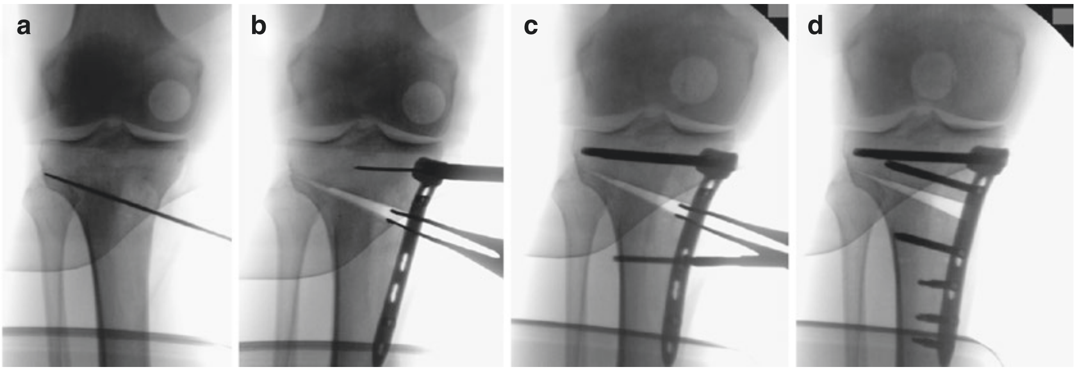

Fig. 46.6 Intraoperative views of valgus-extension osteotomy surgical technique details. (**a**) Hinge at lateral cortex is intentionally broken with osteotome. (**b**) Gap opened with bone spreader, plate positioning, instable hinge. (**c**) Hinge stabilization through compression screw insertion. (**d**) Final configuration after plate fixation and removal of compression screw

obtained at the 6-week postoperative appointment. If there is evidence of consolidation, the brace is discontinued and full weight-bearing is initiated with a strengthening program. At the 10-week postoperative appointment, radiography is repeated. If osseous consolidation has been achieved, sport-specific rehabilitation is initiated.

46.9 Closing-Wedge Anterior Deflection High Tibial Osteotomy and ACL Reconstruction

Knee arthroscopy and preparation of the notch are performed including the femoral tunnel using a rear entry guide or anteromedial portal. The tibial tunnel is performed after the osteotomy. An anterior longitudinal incision centered on the anterior tibial tubercle is utilized. The tibial tubercle is detached from the intended tibial osteotomy site as a 6-cm bone block. The closing-wedge osteotomy is performed according to the preoperative calculation. Under fluoroscopic control, one or two K-wires are inserted from anterior to posterior to mark the osteotomy site, starting about 3–4 cm distal to the joint line, parallel to the posterior tibial slope (PTS) (Fig. 46.7a). Keeping an intact posterior bony bridge is critical to protect the popliteal structures and limits the risk of secondary displacement or pseudarthrosis (Fig. 46.7b). The aim is to obtain a PTS of between 0 and 10° depending on the severity of the deformity and the knee motion. The anterior closing-wedge osteotomy is fixed with two staples or two "8" epiphysiodesis plates positioned medially and laterally with respect to the tibial tubercle. The tibial tubercle is repositioned by translating it distally with an amount equal to the thickness of the removed bony fragment to prevent postoperative change of patellar height, and it is fixed with two anteroposterior cortical screws: one above and the other below the osteotomy site (Fig. 46.7c). The tibia tunnel is then drilled in the standard fashion. Graft is passed from distal to proximal and secured with suture button fixation or screws (Fig. 46.8). Rehabilitation is similar to what is stated above.

46.10 Outcomes of Osteotomy for ACL Instability

Isolated HTO for the treatment of ACL instability has been rarely described. In 1993, Noyes et al. [41] reported the outcomes of closing-wedge lateral HTO for the treatment of 41 complex patients with chronic ACL deficiency and varus malalignment, mostly with medial joint degeneration or failed previous ACL reconstruction. Eleven of

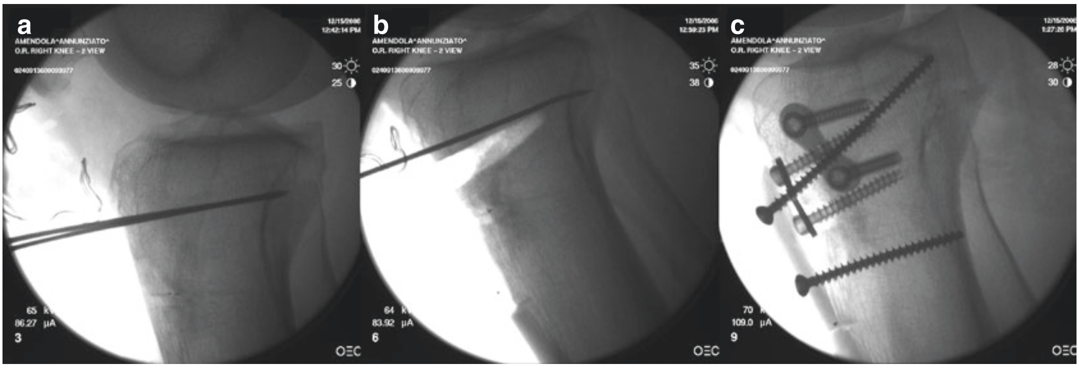

Fig. 46.7 Principal steps of a deflection anterior closing-wedge HTO. To guide the osteotomy cut after tibial tuberosity detachment, 1 or 2 K-wires are positioned, under fluoroscopic control, from anterior to posterior starting about 3–4 cm distal to the joint line, parallel to the posterior tibial slope (**a**). A posterior bony bridge is kept intact to protect the popliteal structures and limits the risk of secondary displacement or pseudarthrosis (**b**). After the planned resection have been performed, the osteotomy is fixed with 2 "8" epiphysiodesis plates and the anterior tibial tubercle translated distally and fixed with two anteroposterior cortical screws, one above and the other below the osteotomy site (**c**)

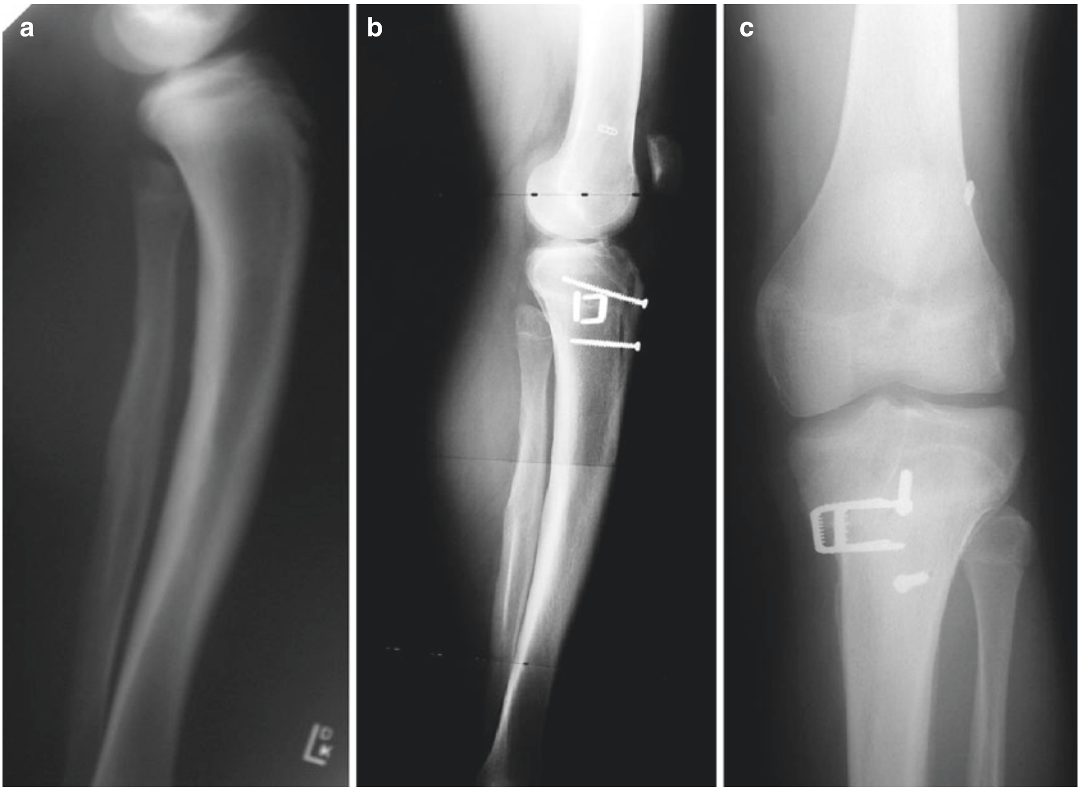

Fig. 46.8 Anteroposterior and lateral radiographs of a 16-year-old male patient with ACL tear. Preoperative lateral radiography shows an increased posterior tibial slope with evident anterior tibial subluxation (**a**). After deflection anterior closing-wedge HTO and ACL reconstruction, it is possible to appreciate the correction of tibial slope and tibial subluxation (**b**), with no alteration of coronal alignment (**c**)

them, mostly those with advanced medial OA and lower functional requests, reported satisfactory results with isolated HTO and activity modification. However, the more active patients required a staged stabilizing procedure to overcome the giving-way sensation. A few years later, Latterman and Jakob [31] treated 30 patients with chronic anterior instability, varus malalignment, and medial OA. The decision to perform isolated HTO or combined/staged ACL reconstruction was based on the patient's level of pain, degree of instability, age, type of previous operative procedures, and amount of activity. Generally, a high patient activity and high degree of instability-related symptoms (i.e., giving way) and younger age (<40 years) were predominant factors for a decision toward a combined treatment. The 11 patients that underwent isolated procedure had significant improvement of pain and symptoms, with anteroposterior and rotatory instability in only two and three cases, respectively, probably due to the stabilizing effect of the degenerative joint condition in these cases. Those treated with a combined procedure however did not show superior outcomes, but rather presented a noticeable rate of complications. These results allowed the authors to suggest the following: primarily consider HTO and combined ACL reconstruction only if instability is the main symptom, while if giving way is not the major complaint, HTO alone could suffice.

Despite these cautious approaches, combined HTO and ACL reconstruction is currently a rather common procedure. A recent systematic review [9] indicated 13 case series describing the outcomes of this surgical approach for 321 patients with anterior laxity and varus osteoarthritis. At a pooled follow-up of almost 5 years, significant improvement of pain and function was reported, with return to various grades of physical activity in 50–60 % of the cases. Complications were registered in 18 % of cases, mostly due to stiffness, necessity of re-osteotomy, or deep venous thrombosis. Good control of anteroposterior laxity was obtained with the procedure, as the mean postoperative side-to-side difference was 2.4 mm and the failure rate was 6 %. Despite the load redistribution, progression to severe medial knee OA was noted in almost 10 % of the patients. Marriott et al. [36] reported the change in gait biomechanics after concomitant HTO and ACL reconstruction, comparing the surgical cases to the nonoperative ones. After 5 years from surgery, patients showed substantial changes during walking, with a substantial decrease in the knee adduction moment in the surgical limb and a slight increase in the nonsurgical limb, together with a decrease in the knee flexion moment for both the surgical and nonsurgical limbs. Since the external knee adduction moment is considered an index for the medial-lateral load distribution across the knee [27, 29], and the knee flexion moment represents the flexor-extensor muscle contraction [46], results from this study are consistent with a load shift toward the lateral compartment without increasing the total load.

Regarding the patients with ACL deficiency and double- or triple-varus deformity, satisfactory results were presented by Noyes et al. [40] and Badhe et al. [4] with HTO and staged or combined ACL reconstruction. However, those with severe deformity and posterolateral insufficiency required a subsequent posterolateral plasty or reconstruction.

The choice for a closing or opening-wedge osteotomy technique in the case of ACL deficiency and varus malalignment can be viewed from an anatomical and biomechanical standpoint. Due to the cross-sectional triangular shape of the proximal tibia, it is intuitive to realize how the removal of a bone wedge from the anterolateral side of the tibia in a closing-wedge osteotomy would decrease the posterior tibial slope, while the distraction in an anteromedial opening-wedge osteotomy would increase the posterior tibial slope. This effect, demonstrated by large case series [19], could therefore suggest a closing-wedge lateral HTO as more suitable in case of a concomitant anteroposterior laxity. However, a recent meta-analysis of 27 studies [39] showed how posterior slope is increased by only 2.02° with an opening-wedge HTO and decreased by only 2.35° with a closing-wedge HTO, thus suggesting that the small magnitude of changes may have little effect on the biomechanics of the cruciate ligaments. In addition, technical precautions to minimize slope changes have been discussed by many authors. As the anteroposterior position of the wedge, the lateral hinge axis, and the ratio between anterior and posterior distraction have been correlated to slope changes [38, 43], a posterior placement of bone spreaders intraoperatively and posterior positioning of wedges which may be used for gap filling is recommended to avoid increasing the slope magnitude. Similarly, the complete osteotomy of posterior cortex and the distraction of the posterior gap have been demonstrated effective in maintaining the tibial slope in both uni- and biplanar opening-wedge HTO [33, 54].

Regarding the treatment of ACL deficiency through slope correction, the available clinical evidence is scant. Although the aim of Arun et al. [3] was not to primarily correct posterior tibial slope, but rather to correct valgus malalignment with medial OA and ACL deficiency, they reported a certain degree of posterior slope decrease with an opening-wedge HTO placing the iliac crest graft and the plate posteriorly, combined with quadrupled hamstring ACL reconstruction. They reported a higher improvement of subjective IKDC and Lysholm score and significantly higher postoperative values in patients with a slope decrease >5° compared to those with a minimal slope correction. Similarly, Zaffagnini et al. [56] reported a significant direct correlation between posterior tibial slope and anteroposterior knee laxity measured with KT-1000 after a closing-wedge HTO and ACL reconstruction in 32 varus-angulated ACL-deficient knees, suggesting a higher postoperative laxity in patients with and a steeper posterior tibial slope. Sonnery-Cottet et al. [49] conversely reported the results of an ACL revision combined with an HTO, primarily aimed to correct pathological posterior tibial slope in patients with multiple previous failures of ACL reconstruction, neutral alignment, and no concomitant injuries of other ligaments. The five patients, all with a posterior tibial slope >13° and a mean side-to-side difference at knee laxity of 10.4 mm, underwent an anterior deflection closing-wedge HTO using the technique described above, and the surgery was completed with a revision ACL reconstruction with an available graft. The authors, at a mean follow-up of 31 months, reported a significant decrease of posterior tibial slope to a mean value of 9.2°, a decrease of anterior laxity to a mean value of 2.8 mm, and no high-grade rotatory instability and improvement of subjective scores, which allowed the patients to even return to sporting activity. Similar results at 4-year follow-up were obtained by Dejour et al. [18] on nine patients treated with second ACL revision reconstruction and an anterior deflection closing-wedge HTO performed above the patellar tendon insertion without tibial tubercle detachment. The authors, which reported a higher slope correction from 13.2 to 4.4°, were able to obtain good subjective results, no anteroposterior or rotatory laxity, and an improvement of side-to-side difference at KT-1000 from 11.7 to 4.3 mm with only minimal changes of patellar height and OA progression.

Conclusion

Based on the current anatomical, biomechanical, and clinical evidence, HTO represents an evidence-based option for the treatment of ACL instability and varus malalignment with or without medial knee OA, in order to minimize the risk of failure of isolated ACL reconstruction and persistent postoperative symptoms. A general consensus on what is the optimal surgical technique is difficult to determine from the literature. However, there is consensus that the osteotomy should provide an accurate coronal and sagittal correction with stable fixation, while preventing an unintended alteration of the posterior tibial slope.

Deflection anterior closing-wedge HTO with or without tibial tubercle detachment, combined with revision ACL reconstruction, is an option that should be considered for the treatment of multiple-failed ACL reconstruction with no bony or ligamentous abnormalities other than posterior slope >10–13°. However, due to the technical complexity of the surgical procedure and the lack of solid clinical evidence, it should be performed carefully only after accurate patient selection and counseling, preoperative planning, intraoperative technical caution, and careful follow-up.

References

1. Agneskirchner JD, Hurschler C, Stukenborg-Colsman C et al (2004) Effect of high tibial flexion osteotomy on cartilage pressure and joint kinematics: a biomechanical study in human cadaveric knees. Winner of the AGA-DonJoy Award 2004. Arch Orthop Trauma Surg 124:575–584
2. Ajuied A et al (2014) Anterior cruciate ligament injury and radiologic progression of knee osteoarthritis: a systematic review and meta-analysis. Am J Sports Med 42(9):2242–2252
3. Arun GR, Kumaraswamy V, Rajan D, Vinodh K, Singh AK, Kumar P, Chandrasekaran K, Santosh S, Kishore C (2016) Long-term follow up of single-stage anterior cruciate ligament reconstruction and high tibial osteotomy and its relation with posterior tibial slope. Arch Orthop Trauma Surg. 136(4):505–11 [Epub ahead of print]
4. Badhe NP, Forster IW (2002) High tibial osteotomy in knee instability: the rationale of treatment and early results. Knee Surg Sports Traumatol Arthrosc 10(1):38–43
5. Blanke F, Kiapour AM, Haenle M, Fischer J, Majewski M, Vogt S, Camathias C (2016) Risk of noncontact anterior cruciate ligament injuries is not associated with slope and concavity of the tibial plateau in recreational alpine skiers: a magnetic resonance imaging-based case-control study of 121 patients. Am J Sports Med. pii: 0363546516632332
6. Bonasia DE, Dragoni M, Amendola A (2014) Osteotomy for malalignment following failed ACL reconstruction. In: Marx RG (ed) Revision ACL reconstruction: indications and technique. Springer, New York
7. Bonin N, Ait Si Selmi T, Donell ST et al (2004) Anterior cruciate reconstruction combined with valgus upper tibial osteotomy: 12 years follow-up. Knee 11:431–437
8. Brinkman JM, Lobenhoffer P, Agneskirchner JD, Staubli AE, Wymenga AB, Van Heerwaarden RJ (2008) Osteotomies around the knee: patient selection, stability of fixation and bone healing in high tibial osteotomies. J Bone Joint Surg (Br) 90:1548–1557

9. Cantin O, Magnussen RA, Corbi F, Servien E, Neyret P, Lustig S (2015) The role of high tibial osteotomy in the treatment of knee laxity: a comprehensive review. Knee Surg Sports Traumatol Arthrosc 23(10): 3026–3037
10. Christensen JJ, Krych AJ, Engasser WM, Vanhees MK, Collins MS, Dahm DL (2015) Lateral tibial posterior slope is increased in patients with early graft failure after anterior cruciate ligament reconstruction. Am J Sports Med 43(10):2510–2514
11. Chun YM, Kim SJ, Kim HS (2008) Evaluation of the mechanical properties of posterolateral structures and supporting posterolateral instability of the knee. J Orthop Res 26:1371–1376
12. Claes S, Hermie L, Verdonk R, Bellemans J, Verdonk P (2013) Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta-analysis. Knee Surg Sports Traumatol Arthrosc 21(9):1967–1976
13. Coventry MB (1985) Upper tibial osteotomy for osteoarthritis. J Bone Joint Surg Am 67:1136–1140
14. Crawford SN, Waterman BR, Lubowitz JH (2013) Long-term failure of anterior cruciate ligament reconstruction. Arthroscopy 29(9):1566–1571
15. Dare DM, Fabricant PD, McCarthy MM, Rebolledo BJ, Green DW, Cordasco FA, Jones KJ (2015) Increased lateral tibial slope is a risk factor for pediatric anterior cruciate ligament injury: an MRI-based case-control study of 152 patients. Am J Sports Med 43(7):1632–1639
16. Dejour H, Bonnin M (1994) Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. J Bone Joint Surg B 76(5): 745–749
17. Dejour H, Neyret P, Boileau P et al (1994) Anterior cruciate reconstruction combined with valgus tibial osteotomy. Clin Orthop Relat Res 299:220–228
18. Dejour D, Saffarini M, Demey G, Baverel L (2015) Tibial slope correction combined with second revision ACL produces good knee stability and prevents graft rupture. Knee Surg Sports Traumatol Arthrosc 23(10):2846–2852
19. Ducat A, Sariali E, Lebel B, Mertl P, Hernigou P, Flecher X et al (2012) Posterior tibial slope changes after opening- and closing-wedge high tibial osteotomy: a comparative prospective multicenter study. Orthop Traumatol Surg Res 98(1):68–74
20. Dugdale TW, Noyes FR, Styer D (1992) Preoperative planning for high tibial osteotomy. The effect of lateral tibiofemoral separation and tibiofemoral length. Clin Orthop Relat Res 274:248–264
21. Giffin JR, Vogrin TM, Zantop T, Woo SL, Harner CD (2004) Effects of increasing tibial slope on the biomechanics of the knee. Am J Sports Med 32(2):376–382
22. Grassi A, Zaffagnini S, Marcheggiani Muccioli GM, Roberti Di Sarsina T, Urrizola Barrientos F, Marcacci M (2016) Revision anterior cruciate ligament reconstruction does not prevent progression in one out of five patients of osteoarthritis: a meta-analysis of prevalence and progression of osteoarthritis. J ISAKOS Joint Disord Orthop Sports Med 1(1):16–24
23. Hashemi J, Chandrashekar N, Mansouri H, Gill B, Slauterbeck JR, Schutt RC Jr, Dabezies E, Beynnon BD (2010) Shallow medial tibial plateau and steep medial and lateral tibial slopes: new risk factors for anterior cruciate ligament injuries. Am J Sports Med 38(1):54–62
24. Hohmann E, Bryant A, Reaburn P, Tetsworth K (2011) Is there a correlation between posterior tibial slope and non-contact anterior cruciate ligament injuries? Knee Surg Sports Traumatol Arthrosc 19(Suppl 1):S109–S114
25. Hsu RW, Himeno S, Coventry MB, Chao EY (1990) Normal axial alignment of the lower extremity and load-bearing distribution at the knee. Clin Orthop Relat Res (255):215–227
26. Hudek R, Schmutz S, Regenfelder F, Fuchs B, Koch PP (2009) Novel measurement technique of the tibial slope on conventional MRI. Clin Orthop Relat Res 467:2066–2072
27. Hurwitz DE et al (1998) Dynamic knee loads during gait predict proximal tibial bone distribution. J Biomech 31(5):423–430
28. Kiapour A, Kiapour AM, Kaul V, Quatman CE, Wordeman SC, Hewett TE, Demetropoulos CK, Goel VK (2014) Finite element model of the knee for investigation of injury mechanisms: development and validation. J Biomech Eng 136(1):011002
29. Kutzner I, Trepczynski A, Heller MO, Bergmann G (2013) Knee adduction moment and medial contact force – facts about their correlation during gait. PLoS ONE 8(12):e81036. doi:10.1371/journal.pone.0081036
30. LaPrade RF, Engebretsen L, Johansen S et al (2008) The effect of a proximal tibial medial opening wedge osteotomy on posterolateral knee instability: a biomechanical study. Am J Sports Med 36:956–960
31. Lattermann C, Jakob RP (1996) High tibial osteotomy alone or combined with ligament reconstruction in anterior cruciate ligament-deficient knees. Knee Surg Sports Traumatol Arthrosc 4(1):32–38
32. Lecuire F, Lerat JL, Bousquet G, Dejour H, Trillat A (1980) The treatment of genu recurvatum (author's transl). Rev Chir Orthop Reparatrice Appar Mot 66(2):95–103
33. Lee YS, Kang JY, Lee MC, Oh WS, Elazab A, Song MK (2016) Effect of the osteotomy length on the change of the posterior tibial slope with a simple distraction of the posterior gap in the uni- and biplanar open-wedge high tibial osteotomy. Arthroscopy 32(2):263–271
34. Li Y, Hong L, Feng H, Wang Q, Zhang J, Song G, Chen X, Zhuo H (2014) Posterior tibial slope influences static anterior tibial translation in anterior cruciate ligament reconstruction: a minimum 2-year follow-up study. Am J Sports Med 42(4):927–933
35. Lipps DB, Oh YK, Ashton-Miller JA, Wojtys EM (2012) Morphologic characteristics help explain the gender difference in peak anterior cruciate ligament

strain during a simulated pivot landing. Am J Sports Med 40(1):32–40

36. Marriott K et al (2015) Five-year changes in gait biomechanics after concomitant high tibial osteotomy and ACL reconstruction in patients with medial knee osteoarthritis. Am J Sports Med 43(9):2277–2285
37. McLean SG, Lucey SM, Rohrer S, Brandon C (2010) Knee joint anatomy predicts high-risk in vivo dynamic landing knee biomechanics. Clin Biomech (Bristol, Avon) 25(8):781–788
38. Moon SW, Park SH, Lee BH, Oh M, Chang M, Ahn JH, Wang JH (2015) The effect of Hinge position on posterior tibial slope in medial open-wedge high tibial osteotomy. Arthroscopy 31(6):1128–1133
39. Nha KW, Kim HJ, Ahn HS, Lee DH (2016) Change in posterior tibial slope after open-wedge and closed-wedge high tibial osteotomy: a meta-Analysis. Am J Sports Med. pii: 0363546515626172
40. Noyes FR, Barber-Westin SD, Hewett TE (2000) High tibial osteotomy and ligament reconstruction for varus angulated anterior cruciate ligament-deficient knees. Am J Sports Med 28:282–296
41. Noyes FR, Barber SD, Simon R (1993) High tibial osteotomy and ligament reconstruction in varus angulated, anterior cruciate ligament-deficient knees. A two- to seven-year follow-up study. Am J Sports Med 21(1):2–12
42. Noyes FR, Schipplein OD, Andriacchi TP, Saddemi SR, Weise M (1992) The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. Am J Sports Med 20(6):707–716
43. Ogawa H, Matsumoto K, Ogawa T, Takeuchi K, Akiyama H (2016) Effect of wedge insertion angle on posterior tibial slope in medial opening wedge high tibial osteotomy. Orthop J Sports Med 4(2): 2325967116630748
44. Phisitkul P, Wolf BR, Amendola A (2006) Role of high tibial and distal femoral osteotomies in the treatment of lateral-posterolateral and medial instabilities of the knee. Sports Med Arthrosc 14:96–104
45. Sabharwal S, Zhao C (2008) Assessment of lower limb alignment: supine fluoroscopy compared with a standing full-length radiograph. J Bone Joint Surg Am 90:43–51
46. Schipplein OD, Andriacchi TP (1991) Interaction between active and passive knee stabilizers during level walking. J Orthop Res 9(1):113–119
47. Song GY, Zhang H, Wang QQ, Zhang J, Li Y, Feng H (2016) Risk factors associated with grade 3 pivot shift after acute anterior cruciate ligament injuries. Am J Sports Med 44(2):362–369
48. Sonnery-Cottet B, Archbold P, Cucurulo T, Fayard JM, Bortolletto J, Thaunat M, Prost T, Chambat P (2011) The influence of the tibial slope and the size of the intercondylar notch on rupture of the anterior cruciate ligament. J Bone Joint Surg (Br) 93(11): 1475–1478
49. Sonnery-Cottet B, Mogos S, Thaunat M, Archbold P, Fayard JM, Freychet B, Clechet J, Chambat P (2014) Proximal tibial anterior closing wedge osteotomy in repeat revision of anterior cruciate ligament reconstruction. Am J Sports Med 42(8):1873–1880
50. Tayton E, Verma R, Higgins B, Gosal H (2009) A correlation of time with meniscal tears in anterior cruciate ligament deficiency: stratifying the risk of surgical delay. Knee Surg Sports Traumatol Arthrosc 17(1):30–34
51. Tunggal JA, Higgins GA, Waddell JP (2010) Complications of closing wedge high tibial osteotomy. Int Orthop 34:255–261
52. Van de Pol GJ et al (2009) Varus alignment leads to increased forces in the anterior cruciate ligament. Am J Sports Med 37(3):481–487
53. Webb JM, Salmon LJ, Leclerc E, Pinczewski LA, Roe JP (2013) Posterior tibial slope and further anterior cruciate ligament injuries in the anterior cruciate ligament-reconstructed patient. Am J Sports Med 41(12):2800–2804
54. Westermann RW, DeBerardino T, Amendola A (2014) Minimizing alteration of posterior tibial slope during opening wedge high tibial osteotomy: a protocol with experimental validation in paired cadaveric knees. Iowa Orthop J 34:16–23
55. Wordeman SC, Quatman CE, Kaeding CC, Hewett TE (2012) In vivo evidence for tibial plateau slope as a risk factor for anterior cruciate ligament injury: a systematic review and meta-analysis. Am J Sports Med 40(7):1673–1681
56. Zaffagnini S, Bonanzinga T, Grassi A, Marcheggiani Muccioli GM, Musiani C, Raggi F, Iacono F, Vaccari V, Marcacci M (2013) Combined ACL reconstruction and closing-wedge HTO for varus angulated ACL-deficient knees. Knee Surg Sports Traumatol Arthrosc 21(4):934–941
57. Zhang Y, Wang J, Xiao J, Zhao L, Li ZH, Yan G, Shi ZJ (2014) Measurement and comparison of tibial posterior slope angle in different methods based on three-dimensional reconstruction. Knee 21(3):694–698

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Criterion-Based Approach for Rehabilitation After ACL Reconstruction

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and Rick Joreitz

47.1 Introduction

Postoperative rehabilitation of anterior cruciate ligament reconstruction (ACLR) progresses in five phases from the time of surgery up to clearance for return to preinjury activity. Every patient will complete the first phase of rehabilitation to resolve impairments and return to normal activities of daily living. Patients may then progress through phases focused on more demanding activities to include running, jumping, hopping, and rotational activities including sports-specific skills based on strict criteria. Not every patient will have the same goals for their postoperative rehabilitation. Therefore, it is the responsibility of the orthopedic sports medicine team, including the surgeon and rehabilitation professional, to determine the ultimate phase of rehabilitation that needs to be completed by each patient. Ultimately, success must be judged on an individual level, specifically based on the desires of the patient.

This chapter will present the protocol developed at the University of Pittsburgh Medical Center (UMPC) Center for Sports Medicine for rehabilitation and return to sports after ACL reconstruction. Recommendations for the return-to-sports phase and prevention of second injury were based on the literature, where available. The clinical decision-making process for return to sports emphasizes structured objective clinical and functional tests and patient-reported outcome measures with associated criteria [4, 21, 41]. While this protocol is evidence based as possible, further research regarding reinjury and successful return to sports is needed to determine the extent of rehabilitation after ACLR [25].

These guidelines are unique in their structured progression of rehabilitation after the immediate postoperative phase, using quantitative and qualitative criteria to progress sports activities. The rehabilitation principles remain the same throughout the rehabilitation process – mastery of basic tasks and progressive demands for demonstrating muscle strength and neuromuscular control. Patients must meet all criteria to progress to the next phase. Exercise selection matches the demands of the current stage and builds upon previous exercises. Balance, proprioception, motor control, agility, and plyometrics training are encouraged to improve performance and limit the risk of secondary injury [8, 15, 16, 26, 28, 36].

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This protocol can be followed in nearly every clinical setting with slight modifications by the physical therapist. No special equipment or facilities are needed for this rehabilitation.

47.2 Assessment of Mastery

Patients must demonstrate mastery of the current phase before progressing to ensure that aberrant and deleterious movement patterns are resolved before beginning more demanding activities. This assessment is qualitative while the patient attempts maximum effort while completing the task, but quantitative measures are included when possible. Based on the visual assessment, patients are given remedial activities and deliberate practice to improve performance.

47.3 Strength Measurement

Adequate quadriceps strength is a critical component of recovery and a predictor of performance in dynamic activities after ACLR [38, 39]. Quadriceps muscle strength deficits may be one of many components to increase risk of a second knee injury after returning to sports participation. When available, isometric or isokinetic dynamometry should be used to measure quadriceps strength, as it isolates the musculature and provides reliable objective measures. In our clinic, quadriceps and hamstrings strength are measured with a maximum volitional isometric contraction for 5 s on an electromechanical dynamometer. To reduce the risk of patellar fractures after patellar or quadriceps graft harvest, isometric strength testing with a dynamometer is delayed until 4 or 5 months postop, and the knee is positioned at 60° of knee flexion to reduce bending forces across the patella.

In cases where dynamometry is not available, strength testing is recommended using a 1 repetition max (1-RM) on a knee extension machine [3, 30]. For the 1-RM leg extension, the individual is positioned with the hip and knee at 90° of flexion, with the resistance pad placed proximally to the malleoli. The individual extends their knee to 45° of knee flexion. If a patient has postoperative restrictions for range of motion (ROM) due to a concomitant injury or surgical procedure, strength testing should not be completed until these restrictions are lifted.

A limb symmetry index (LSI) is calculated as the 1-RM load of the involved limb divided by the 1-RM load of the uninvolved limb multiplied by 100. The leg extension 1-RM test has not been validated compared to isometric dynamometry to measure limb symmetry; however, this testing may be done easily in a clinical setting with standard equipment. The leg extension test is preferred because it isolates the quadriceps musculature and more closely simulates isometric dynamometry testing. Strength testing should occur serially to ensure strength is maintained at the least and ideally progressing.

47.4 Neuromuscular Control

Neuromuscular control is tested with three basic tests with progressive criteria for each phase of rehab. The step and hold is a low-level approximation of running to screen for abnormal mechanics and pain. The patient steps from the uninjured limb onto the injured limb on a flat surface, at least the distance of the individual's normal stride length. The individual must land with a heel-toe gait pattern to simulate walking. The distance is progressed to prepare for running. Individuals must complete 30 step and holds without loss of balance, excessive knee stiffening, or excessive knee flexion (Fig. 47.1: *Step and Hold*). The single-leg squat is performed for ten consecutive repetitions to 45° or greater of knee flexion (depending on the phase of rehabilitation) to screen for deviations (Fig. 47.2: *Single-Leg Squat*). Deviations are operationally defined as the use of compensatory patterns including loss of balance, contralateral hip drop, excessive femoral abduction or adduction, excessive femoral internal rotation, or abnormal trunk movement [33].

The Y-balance test is a measure of stability between limbs that correlates with injury risk [12, 34]. The individual stands facing the stem of a "Y" made of tape on the floor, with two arms extending posterior at 135° clockwise and counterclockwise from the stem. While maintaining single-leg balance and not shifting weight to the opposite limb, the patient reaches as far along each point as

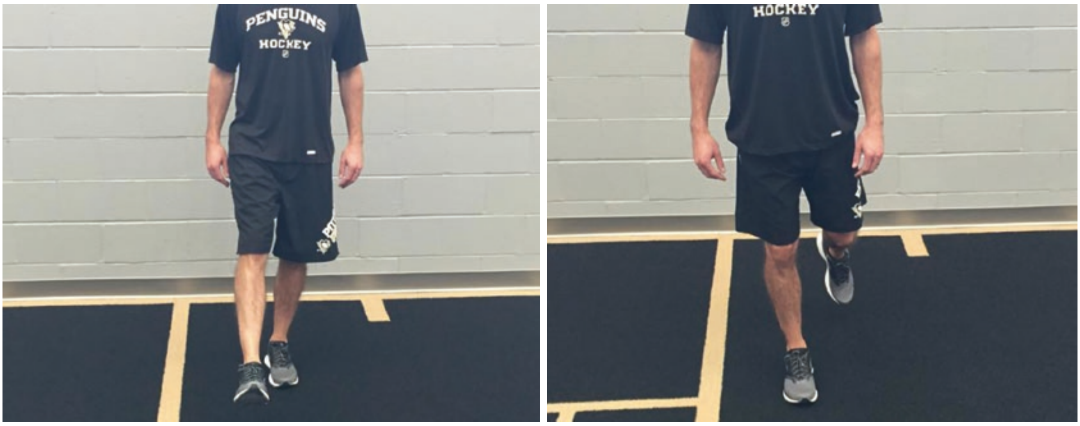

Fig. 47.1 Step and hold. Patients must perform 30 step and holds without loss of balance or excessive motion in the frontal or transverse plane

Fig. 47.2 Single-leg squat. This task is performed to the appropriate prescribed angle of knee flexion for ten repetitions to screen for deviations

possible with the opposite leg limiting gross compensatory patterns (Fig. 47.3: *Y-balance test*). Two practice trials and four measured trials are completed for each direction. The distance is measured from the center of the Y in centimeters to the position of maximum reach. Performance is normalized to leg length measured from the inferior aspect of the anterior superior iliac spine

$$Y - \text{balance composite score} = \frac{(\text{anterior reach} + \text{posteromedial reach} + \text{posterolateral reach})}{(3 \times \text{limb length})}$$

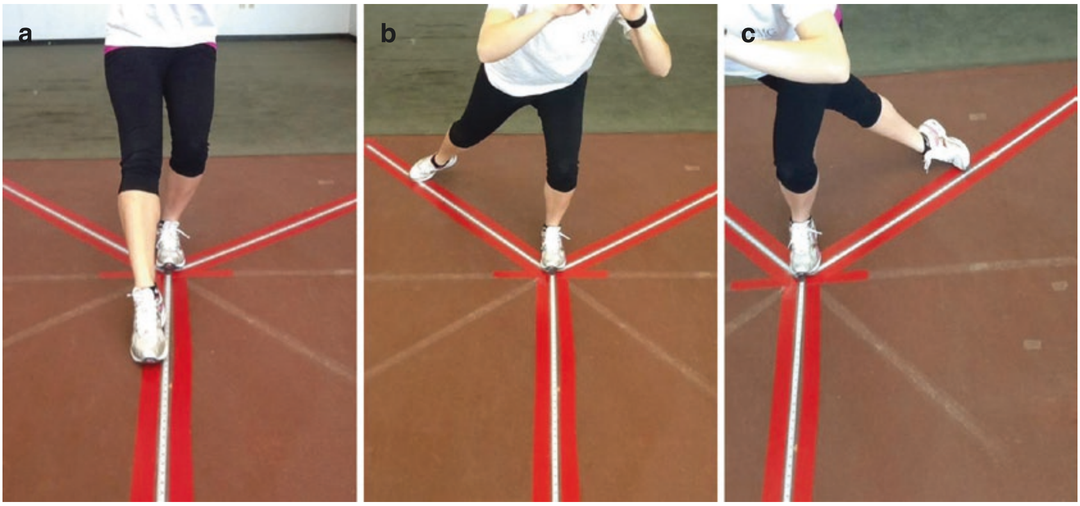

Fig. 47.3 Y-balance test. The individual stands with the toe of the testing foot at the center of the Y and reaches as far along each point as possible without transferring weight to the reach limb. (**a**) Anterior reach on the right leg; (**b**) posteromedial reach on the right leg; (**c**) posterolateral reach on the right leg

to the most prominent aspect of the lateral malleolus. Comparisons between limbs are made for each reached distance and a composite score.

47.5 The UPMC Center for Sports Medicine Functional Training and Return to Sports Rehabilitation Protocol

47.5.1 Phase 1: Immediate Postoperative Rehabilitation

The immediate postoperative rehabilitation begins 2–7 days after surgery depending on the amount of preoperative rehabilitation and education provided. The goals of phase 1 are to (1) prevent ROM loss, (2) promote activation of the quadriceps, (3) reduce the inflammatory process in the knee (swelling and pain), and (4) ensure safe and effective ambulation. Once these primary goals have been achieved, postoperative physical therapy aims to normalize ROM, strength, and daily activity.

After ACLR, the knee joint is significantly inflamed, as evidenced by swelling and postoperative pain. Swelling is associated with both impaired quadriceps activation and limited flexion ROM. Slight knee joint flexion is the position of minimal joint contact and is typically the preferred position of comfort for individuals with pain and swelling. Therefore, patients after ACLR may be unable to achieve full active extension due to poor quadriceps activation and discomfort.

The initial focus of rehabilitation is to achieve active knee joint extension to neutral (0°) with a quadriceps contraction that produces a superior patellar glide. The patient should be positioned sitting on the ground (or a long table) with their legs straight in front of them and nothing underneath the knee joint. The heel may be propped to allow for full extension or mild joint hyperextension. Patellar mobilizations are effective in increasing the available ROM of the patellofemoral joint. Quadriceps activation can be facilitated with simultaneous contraction of the contralateral quadriceps, manual facilitation of a superior patellar glide, or neuromuscular electrical stimulation (NMES) [11]. Care should be taken to avoid common compensations for an inability to activate the quadriceps. Compensations include contraction of the gluteus maximus to extend the femur or dorsiflexion of the ankle joint to create a sensation of tension across the posterior capsule (i.e., perceived stretch by the patient). Low-load, prolonged stretch exercises may be of benefit to the patient who struggles with extension ROM. These exercises may include prone positioning with a weight on the heel to promote extension or a long sitting position (as described above) with the heel propped on a bolster. These exercises may be used but care should be taken to ensure that the patient is able to relax enough to allow extension to occur. Patients who do not achieve neutral extension by the end of postoperative week 2 or extension within 3° of the contralateral limb by 4 weeks postoperative should be referred back to their treating surgeon for evaluation.

Flexion ROM can be increased with active ROM exercises and active assisted ROM exercises (e.g., heel slides). For individuals with hamstring autograft ACLR, care should be taken early after surgery to avoid resisted or strenuous activation of the hamstrings while healing occurs. For individuals who are unable to increase ROM independently with active and active assisted ROM exercises, patellofemoral joint mobilizations are beneficial. Specifically, inferior joint mobilizations replicate the normal arthrokinematics of knee joint flexion. Medial patellar joint mobilizations may also be helpful when knee joint effusion forces the patella to deviate laterally during knee joint flexion. Patients who do not achieve 90° flexion by the end of postoperative week 2 or 120° by 4 weeks postoperative should be referred back to their treating surgeon for evaluation, if a regularly scheduled appointment does not already exist.

To promote increases of ROM, it is also important to reduce the overall amount of swelling in the knee joint. Aside from potential pharmacological intervention from the medical provider, the rehabilitation professional can assist the process through the application of compression and elevating the limb. Cryotherapy is also of benefit to decrease inflammation and control pain. Effusion should be tracked with the modified stroke test [40], with an expectation that the patient achieve a grade of 2+ between weeks 2 and 4 postoperative and a 1+ by week 8.

Patients with noncomplicated ACLR (i.e., no meniscus repair or chondral surgery) should be encouraged to assume a normal gait as soon as possible after surgery. Depending on surgeon preference and recommendation, patients may be issued a postoperative brace and/or assistive device. To initiate the normal gait cycle, exercises such as terminal knee extension to simulate the midstance phase of gait and weight shifts to simulate initial contact and weight acceptance can be implemented. As the patient demonstrates a consistent, normal step through gait without pain or excessive aberrant movements, they can discontinue crutch use. Until gait is completely normal, they should use the crutches with weight bearing as tolerated to practice a normal walking pattern. Patients are recommended to use the postoperative brace in crowded or uncertain situations (e.g., inclement weather).

The primary strength focus of postoperative rehabilitation is for the quadriceps muscle in both weight-bearing and non-weight-bearing exercises. Non-weight-bearing exercise is crucial to isolate the quadriceps muscle. There is concern that non-weight-bearing knee extension exercises may put excess stress on the reconstructed ACL due to anterior tibial shear. However, limiting the ROM to between 90 and 45° of knee flexion limits that anterior strain [9]. Weight-bearing exercises in the 45° to 0° ROM also produce limited strain on the graft. Therefore, these range restrictions are imposed for the first 8–12 weeks after ACLR, after which the ranges of motion are slowly increased. Weight-bearing exercises typically reflect the demands of daily activities to improve performance in those tasks (e.g., step-ups, step-downs, sit to stand). Various versions of squats and leg presses may also be used. Any irritation to the patellofemoral joint should be treated with specific patellar mobilizations to increase mobility, stretching exercises for the quadriceps especially the rectus femoris, and additional strengthening of the quadriceps. All exercises should be pain-free, and the patient should not complain of pain after therapy.

In addition to the quadriceps, the other lower-extremity muscles affecting the knee joint should be strengthened as needed. The hip abductors, external rotators, and extensors are important for dynamic control of the femur. The calf muscles, especially the muscles to dynamically support the arch of the foot, are also important to control the tibia. As a general treatment approach, abdominal and lumbar strength should be targeted with specific exercise to limit aberrant trunk motions which influence the demands on the knee joint.

47.5.2 Phase 2: Running

Running on a treadmill or track provides controlled environment to systematically increase the load placed on the knee joint between 3 and 5 months after ACLR. Progression to the running phase is only allowed after mastery of phase 1 has been determined. This includes symmetrical ROM, trace or less knee joint effusion, and minimal gait deviations during fast treadmill walking. Gait deviations including decreased stride length, contralateral pelvic drop, femoral internal rotation, and medial collapse of the knees while walking indicate the patient is not ready for running. The patient must then complete a Y-balance test composite score of at least 90 %, 30 step and holds, and 10 consecutive single-leg squats on the involved leg to at least 45° of knee flexion without compensatory patterns. Finally, the individual must demonstrate 80 % quadriceps muscle strength symmetry.

When the patient achieves the criteria without increased pain or inflammation, a run-walk progression is implemented with progressive increases in distance (see example in Adams et al. [1]). The authors advocate a distance-based progression rather than a time-based progression to more accurately monitor knee joint loading during this phase. When an appropriate running gait pattern is consistently observed, the individual can complete the running progression independently.

47.5.3 Phase 3: Basic Agility Drills

To demonstrate mastery of phase 2, the individual must be able to run 2 miles continuously without any complaints of pain, signs or increased swelling, and without gait deviations. Neuromuscular control is tested with 10 consecutive weighted single-leg squats to 45° of knee flexion without aberrant movements with a limb symmetry index of greater than or equal to 75 % and a Y-balance test with a composite score of at least 100 %. Individuals must also demonstrate greater than or equal to 85 % LSI for quadriceps strength.

Once these tests are passed, the individual can begin agility training. Basic agility drills include straight plane movements (anteroposterior and lateral), such as shuttle running, side shuffling, carioca (lateral shuffling while crossing your trail leg over the lead leg), and agility drill ladder exercises or small agility hurdles in forward and

Criteria to Start Jogging at 4–6 Months Post-Op

- No abnormal gait patterns while walking as fast as they can on the treadmill for 15 min
- Thirty step and holds without loss of balance or excessive motion outside of the sagittal plane
- Ten consecutive single-leg squats to 45° of knee flexion without deviation
- ≥80 % 1-repetition maximum (1-RM) on the knee extension machine (90–45°)
- ≥90 % composite score on Y-balance test

Criteria to Start Agility Training

- Be able to run 2 miles continuously without pain, swelling, warmth, or gait deviations
- Ten consecutive single-leg squats >45° of knee flexion without deviation while holding ≥75 % extra weight compared to the other side (dumbbells, weight vest, etc.)
- ≥85 % 1-RM on the knee extension machine (90–45°) or Biodex testing if available
- One hundred percent composite score on Y-balance test

lateral directions. Direction changes with appropriate hip and knee flexion to absorb the load are emphasized. To promote safe movements, effort begins at approximately 50 % speed and progresses as performance improves. Compensatory patterns should be quickly resolved with cueing from the physical therapist.

47.5.4 Phase 4: Double-Limb Jumping

To demonstrate mastery of phase 3 (low-level agility drills), the patient must complete forward/backward shuffling, side shuffling, carioca, and ladder drills at full speed without compensation patterns. Individuals must also demonstrate adequate neuromuscular control by performing ten consecutive weighted single-leg squats to at least 60° of knee flexion with a limb symmetry index of at least 85 % and demonstrate quadriceps muscle strength symmetry of greater than or equal to 90 % LSI.

Phase 4 of rehabilitation includes double-limb jumping, in which the individual begins with forward jumps, lateral jumps, and rotational jumps. Progression to ascending and descending box jumps is at the discretion of the physical therapist. Rebounding jumps and combination movements are the final stage of progression. The patient must avoid abnormal frontal and transverse plane movements (dynamic valgus) and should be cued to exaggerate hip and knee flexion with a soft and quiet landing with equal weight distribution for takeoff and landing [8, 15, 26, 32].

Criteria to Start Jumping

- No compensation patterns with deceleration during agility drills performed at near 100 % effort.
- Ten consecutive single-leg squats to 60° of knee flexion without deviation while holding ≥85 % extra weight compared to the other side (dumbbells, weight vest, etc.). Body weight is not part of the equation.
- ≥90 % 1-RM on the knee extension machine (90–45°) or Biodex testing if available.

47.5.5 Phase 5: Single-Limb Hopping and Cutting and Sports-Specific Drills

The patient must demonstrate mastery of rebound and combination jumps without compensations. To demonstrate neuromuscular control, individuals must perform ten consecutive weighted single-leg squats to at least 60° of knee flexion with a limb symmetry index of greater than or equal to 90 % and demonstrate quadriceps muscle strength symmetry of greater than or equal to 90 % LSI (Table 47.1).

In phase 5, hopping drills follow the same progression as jumping drills in phase 4. Rotational demands are added with cutting and pivoting drills including running in an “S” pattern or a figure of 8, progressing to 45° cuts, and then to sharper angle cuts. Pivoting should begin when the individual is competent with cutting at sharp angles. Similar to phases 2–4, confidence and performance dictate the speed of cutting and pivoting drills, and the individual should not progress to high-level cutting and pivoting drills if they demonstrate compensatory patterns or poor confidence [7]. The final aspect of these drills is to perform unanticipated cutting, pivoting, and hopping (i.e., reactionary drills). Once the individual performs these drills with confidence and at pace, rehabilitation will solely focus on the specific demands needed to return to sports.

Criteria to Start Hopping and Cutting

- No display of medial collapse of the knees when loading into or landing from jumps and equal weight distribution when initiating and landing the jumps.
- Ten consecutive single-leg squats to 60° without deviation while holding ≥90 % extra weight compared to the other side (dumbbells, weight vest, etc.). Body weight is not part of the equation.
- ≥90 % 1-RM on the knee extension machine (90–45°) or Biodex testing if available.

Table 47.1 Criteria to advance to each new phase

Criteria to enter phase 2 – running:		
Phase 1 mastery	Symmetrical ROM, minimal knee joint effusion (trace or less)	
	Maximal treadmill walking ×15 min without deviations[a]	
Neuromuscular control	Step and hold	30 repetitions without deviation[a]
	Single-leg squats	10 repetitions to 45° of knee flexion without deviation[a]
	Y-balance test[b]	≥90 % composite score
Quadriceps strength	Strength battery	Leg extension ≥80 % 1-RM LSI (90–45°)
	OR	
	Isometric dynamometry	≥80 % limb symmetry index
Criteria to enter phase 3 – low-level agility drills:		
Phase 2 mastery	Run 2 miles continuously without pain, swelling, warmth, or gait deviations	
Neuromuscular control	Single-leg squats[c]	10 repetitions to >45° of knee flexion without deviation[a] and 75 % LSI
	Y-balance test[b]	≥100 % composite score
Quadriceps strength	Strength battery	Leg extension ≥85 % 1-RM LSI[d] (90–45°)
	OR	
	Isometric dynamometry	≥85 % limb symmetry index
Criteria to enter phase 4 – double-leg jumping:		
Phase 3 mastery	No compensation patterns with deceleration during phase 3 agility drills performed at full speed	
Neuromuscular control	Single-leg squats[c]	10 repetitions to 60° of knee flexion without deviation[a] and 85 % LSI
Quadriceps strength	Strength battery	Leg extension ≥90 % 1-RM LSI (90–45°)
	OR	
	Isometric dynamometry	≥90 % limb symmetry index
Criteria to enter phase 5 – single-leg hopping and cutting:		
Phase 4 mastery	No deviations when initiating and landing jumps	
Neuromuscular control	Single-leg squats[c]	10 repetitions to 60° of knee flexion without deviation[a] and 85 % LSI
Quadriceps strength	Strength battery	Leg extension ≥90 % 1-RM LSI (90–45°)
	OR	
	Isometric dynamometry	≥90 % limb symmetry index

[a] Deviations include loss of balance, excessive motion outside of the sagittal plane, abnormal trunk movement, contralateral pelvic drop, femoral internal rotation, and medial collapse of the knees

[b] *Y*-balance test composite score: $\frac{\text{Anterior reach} + \text{posteromedial reach} + \text{posterolateral reach}}{3 \times \text{limb length}} \times 100\%$

[c] Single-limb squat limb symmetry index: $\frac{\text{External load during involved limb single leg squat}}{\text{External load during uninvolved limb single leg squat}} \times 100\%$

[d] 1-RM LSI: $\frac{\text{Inovolved limb } 1 - \text{RM}}{\text{Uninvolved limb } 1 - \text{RM}} \times 100\%$

47.6 Return-to-Practice Testing and Return to Sports

Return-to-practice testing occurs when the individual can run and perform all agility, plyometrics, and sports-specific drills without any hesitation and compensatory patterns and with no complaints of pain, instability, or signs or symptoms of inflammation. The battery of return-to-sports testing (Table 47.2) includes a strength assessment, functional testing for symmetrical performance, and functional testing for running situations. Individuals must demonstrate greater than or equal to 90 % quadriceps LSI to pass the

Table 47.2 Post-op ACL reconstruction return-to-sports test

Post-op ACL reconstruction return-to-sports testing				
Quadriceps strength	**Involved limb**	**Uninvolved limb**	**Limb symmetry index**	**Passing score**
1-RM on the knee extension machine or Biodex testing				≥90 %
Hop tests	**Involved limb performance**	**Uninvolved limb performance**	**Limb symmetry index**	
Single-leg forward hop				≥90 %
Single-leg triple hop				≥90 %
Single-leg triple crossover				≥90 %
Timed 6-m single leg				≥90 %
Single-leg vertical hop				≥90 %
Functional runs	**Patient performance**	**Recommended range for males**	**Recommended range for females**	
10-yard lower-extremity functional test[a]		*18–22 s*	*20–24 s*	
Trial 1				
Trial 2				
10-yard pro-agility run[b]		*4.5–6.0 s*	*5.2–6.5 s*	
Toward injured limb				
Toward uninjured limb				

[a] Lower-extremity functional test

Sprint/back-peddle, shuffle, carioca, sprint

Must perform at perceived full speed and not display hesitation or compensation strategies when decelerating

[b] 10-yard pro-agility test

Must perform at perceived full speed and not display hesitation or compensation strategies when decelerating

Criteria to Return to Practice

MD clearance

Pass return-to-sports test with ≥90 % results for each test

Criteria to Return to Competition

MD clearance

Tolerate full practice sessions with opposition and contact (if applicable) performed at 100 % effort without any increased pain, increased effusion, warmth, or episodes of giving way

return-to-sports testing. Once adequate strength is determined, functional testing is completed.

47.7 Objective Functional Symmetry Testing

Functional testing batteries are becoming more prevalent [13, 14, 23, 24, 29, 41, 42]. Unilateral hop tests correlate with quadriceps strength measures [23, 24], but do not eliminate the need for isolated testing of the quadriceps [39]. Early functional testing with hop tests can be predictive of self-reported normal knee function at 1 year after ACLR [23]. Unilateral hop test batteries are used to challenge strength and stability in a repeatable manner in the clinic, using the opposite limb as a benchmark [13, 14, 23, 24, 29, 31, 41]. Limb symmetry indexes of greater than or equal to 85 % [5], 90 % [13, 14, 23, 24, 29], and

95 % to 100 % [41, 42] have been used to indicate "normal" or symmetrical performance and used for clearance to return to sports. These cutoffs have not been validated as predictors of safe return to play. The authors recommend the use of greater than or equal to 90 % limb symmetry of hop test measures as an adequate cutoff for clearance to return to sport. A LSI threshold of 90 % is used as opposed to 95 or 100 % as recommended by the European Sports Rehabilitation Board [41] as these thresholds may be too stringent and unattainable for some individuals.

The Noyes' hop series has been well described and involves four tests: the single hop for distance, the triple hop for distance, the triple crossover hop for distance, and the timed 6 m hop [6, 10, 31, 35]. All takeoffs and landings must occur in single-limb stance without excessive trunk or arm motions for balance. As noted above, involved limb performance is normalized to the uninvolved limb and expressed as a limb symmetry index. Because the uninvolved limb is expected to move the individual more rapidly down the line during the 6 m timed hop, the uninvolved limb is expressed as a percentage of the involved limb to maintain the convention that scores less than 100 % indicate superior performance of the uninvolved limb.

Muscular power is tested with a single-limb vertical hop test. The individual stands next to a wall and jumps as high as possible from one limb, using their preferred countermovement strategy. The landing is uncontrolled, but monitored for compensations. The individual attempts to jump as high as possible, measured by either having the individual put a piece of tape on the wall or using a Vertec System (Gill Athletics, Champaign, IL). Limb performance is expressed as a ratio of the best recorded jump height of three trials on the reconstructed limb compared to the contralateral limb.

47.8 General Functional Agility Testing

Bipedal agility tests are not sufficient to identify asymmetries between limbs [29]. To provide a consistent method for assessing movement quality in bipedal tasks, patients complete two functional runs that focus on quickness and confidence when making direction changes. The lower-extremity functional run (Fig. 47.4a) is set up on a 10-yard (30 ft) course. The athlete begins sprints 10 yards, back pedals 10 yards, plants on the involved limb and shuffles 10 yards in each direction, followed by a 10-yard carioca in each direction, and ends with a final 10-yard sprint. The pro-agility test (Fig 47.4b) involves complete direction changes on both limbs. The athlete begins straddling the center line of a 10-yard course. The athlete must sprint 5 yards and touch the cone, change direction, sprint back 10 yards and touch the cone, change direction, and sprint back through the center line. This is completed in both directions.

After successful completion of the return-to-sports test, the athlete brings the test results to their physician for final clearance. The return to practice should begin with individual drills, followed by controlled contact drills, and eventually team scrimmages. The athlete, coach, physical therapist, and surgeon should be in contact about performance and modifications. Individuals return to their physician for full return-to-competition clearance when they can practice at 100 % effort (with contact if applicable) and have no complaints of pain or signs and symptoms of inflammation.

47.9 Patient-Reported Outcome Measures

Patient-reported outcome measures (PROs) are important measures of patient perception of knee function, activities of daily living, sports performance, and fear of reinjury and movement. The international medical community agrees that PROs are an important component of measuring success after ACLR; however, consensus on which specific measure to use has not been reached [25]. The authors recommended the International Knee Documentation Committee (IKDC) 2000 subjective knee form due do its comprehensive qualities and normative database [2]. The IKDC 2000 is a valid and reliable measure of knee symptoms, knee function, and sports activity in patients with a variety of knee injuries [17]. A relationship has been established between

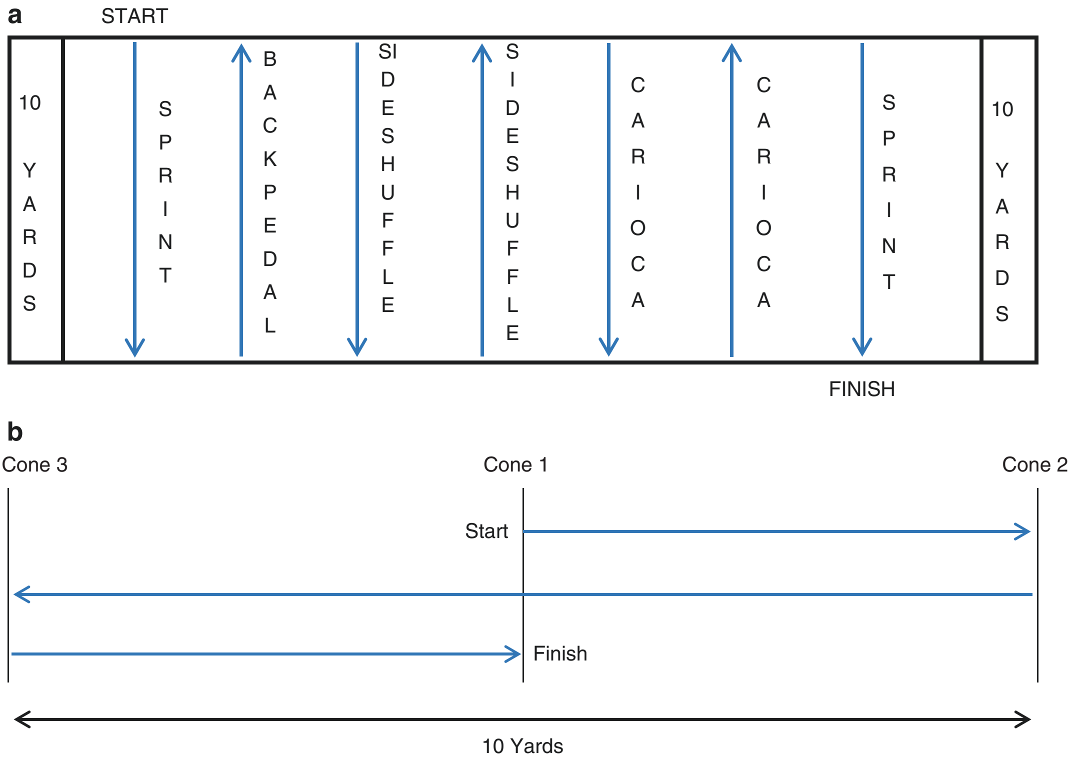

Fig. 47.4 General functional agility runs. (**a**) Lower-extremity functional run. (**b**) Pro-agility test. Patients will sprint 10 yards, then backpedal to the starting line, side shuffle 10 yards and back, carioca 10 yards and back, and finally sprint 10 yards to the finish line. To pass this test, patients must run and change direction at full speed without any compensation patterns. Patients will start facing the tester straddling cone 1. When indicated, they will turn and sprint 5 yards and touch cone 2, then sprint 10 yards and touch cone 3, and finally, sprint 5 yards past cone 1. They will then repeat this test in reverse order (cone 1–3 to 2–1). To pass this test, patients must run and change direction at full speed without any compensatory patterns

the IKDC and measures of quadriceps muscle strength [23, 39], single-leg hop tests [13, 23], and return-to-activity testing [22]. These studies have identified that the IKDC is highly specific, and therefore a lower score on the IKDC is indicative of lower performance on functional testing measures. The IKDC should not be used in place of functional testing; however, a lower score on the IKDC suggests poorer functional performance and should be used as an indicator to further evaluate performance [14].

Increased fear of movement and reinjury have been identified as reasons for not returning to preinjury activities after ACLR [18, 20, 37, 44]. The Tampa Scale for Kinesiophobia (TSK-11) is a pain-related questionnaire used to measure fear of movement and reinjury in patients with chronic musculoskeletal pain [37, 44]. Worse reports on the TSK-11 in ACL-reconstructed individuals were seen in patients who had not returned to their previous level of function [19, 20], compared to those who had returned to activities. The Anterior Cruciate Ligament-Return to Sport after Injury scale (ACL-RSI) was developed to quantitatively evaluate emotions, confidence in performance, and risk appraisal of returning to sports after ACLR [43]. Similar to the TSK-11, individuals who returned to activities report significantly better scores compared to those who do not return to activities [18, 27]. Failing to identify individuals with increased fear of reinjury prior to returning to preinjury activities may put these individuals at increased risk of second knee injury.

Conclusion

These guidelines provide a structure for returning the patient from surgery through rehabilitation. Constant communication and logical decision making are crucial to the success of this protocol and the athlete. Rehabilitation may be stopped at any of the phases if the patient does not need to progress further to meet the demands of their sport or desired level of activity. This guideline for functional testing and rehabilitation progression has been developed to be patient specific with criterion-based milestones.

References

1. Adams D, Logerstedt D, Hunter-Giordano A, Axe MJ, Snyder-Mackler L (2012) Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. J Orthop Sports Phys Ther 42:601–614. http://dx.doi.org/
2. Anderson AF, Irrgang JJ, Kocher MS, Mann BJ, Harrast JJ, International Knee Documentation C (2006) The international knee documentation committee subjective knee evaluation form: normative data. Am J Sports Med 34:128–135. http://dx.doi.org/10.1177/0363546505280214
3. Augustsson J, Thomee R, Karlsson J (2004) Ability of a new hop test to determine functional deficits after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 12:350–356. http://dx.doi.org/
4. Barber-Westin SD, Noyes FR (2011) Factors used to determine return to unrestricted sports activities after anterior cruciate ligament reconstruction. Arthroscopy 27:1697–1705. http://dx.doi.org/
5. Barber SD, Noyes FR, Mangine RE, McCloskey JW, Hartman W (1990) Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. Clin Orthop Relat Res 204–214. http://dx.doi.org/
6. Cascio BM, Culp L, Cosgarea AJ (2004) Return to play after anterior cruciate ligament reconstruction. Clin Sports Med 23:395–408, ix. http://dx.doi.org/
7. Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ (2008) The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation. J Orthop Sports Phys Ther 38:746–753. http://dx.doi.org/
8. Di Stasi S, Myer GD, Hewett TE (2013) Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. J Orthop Sports Phys Ther 43:777–792, A1–11. http://dx.doi.org/
9. Escamilla RF, Macleod TD, Wilk KE, Paulos L, Andrews JR (2012) Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. J Orthop Sports Phys Ther 42:208–220. doi:10.2519/jospt.2012.3768. http://dx.doi.org/
10. Fitzgerald GK, Axe MJ, Snyder-Mackler L (2000) Proposed practice guidelines for nonoperative anterior cruciate ligament rehabilitation of physically active individuals. J Orthop Sports Phys Ther 30:194–203. http://dx.doi.org/
11. Fitzgerald GK, Piva SR, Irrgang JJ (2003) A modified neuromuscular electrical stimulation protocol for quadriceps strength training following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 33:492–501. http://dx.doi.org/10.2519/jospt.2003.33.9.492
12. Gribble PA, Hertel J, Plisky P (2012) Using the star excursion balance test to assess dynamic postural-control deficits and outcomes in lower extremity injury: a literature and systematic review. J Athl Train 47:339–351. http://dx.doi.org/
13. Grindem H, Logerstedt D, Eitzen I et al (2011) Single-legged hop tests as predictors of self-reported knee function in nonoperatively treated individuals with anterior cruciate ligament injury. Am J Sports Med 39:2347–2354. http://dx.doi.org/
14. Hartigan EH, Axe MJ, Snyder-Mackler L (2012) Time line for noncopers to pass return-to-sports criteria after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 40:141–154. http://dx.doi.org/
15. Hewett TE, Di Stasi SL, Myer GD (2013) Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. Am J Sports Med 41:216–224. http://dx.doi.org/
16. Hewett TE, Myer GD, Ford KR, Paterno MV, Quatman CE (2012) The 2012 ABJS Nicolas Andry Award: the sequence of prevention: a systematic approach to prevent anterior cruciate ligament injury. Clin Orthop Relat Res 470:2930–2940. http://dx.doi.org/
17. Irrgang JJ, Anderson AF, Boland AL et al (2001) Development and validation of the international knee documentation committee subjective knee form. Am J Sports Med 29:600–613. http://dx.doi.org/
18. Langford JL, Webster KE, Feller JA (2009) A prospective longitudinal study to assess psychological changes following anterior cruciate ligament reconstruction surgery. Br J Sports Med 43:377–381. http://dx.doi.org/10.1136/bjsm.2007.044818
19. Lentz TA, Zeppieri G Jr, George SZ et al (2015) Comparison of physical impairment, functional, and psychosocial measures based on fear of reinjury/lack of confidence and return-to-sport status after ACL reconstruction. Am J Sports Med 43:345–353. http://dx.doi.org/10.1177/0363546514559707
20. Lentz TA, Zeppieri G Jr, Tillman SM et al (2012) Return to preinjury sports participation following anterior cruciate ligament reconstruction: contributions of demographic, knee impairment, and self-report measures. J Orthop Sports Phys Ther 42:893–901. http://dx.doi.org/10.2519/jospt.2012.4077
21. Logerstedt D, Arundale A, Lynch A, Snyder-Mackler L (2015) A conceptual framework for a sports knee injury

performance profile (SKIPP) and return to activity criteria (RTAC). Braz J Phys Ther 19:340–359. http://dx.doi.org/10.1590/bjpt-rbf.2014.0116

22. Logerstedt D, Di Stasi S, Grindem H et al (2014) Self-reported knee function can identify athletes who fail return-to-activity criteria up to 1 year after anterior cruciate ligament reconstruction: a delaware-oslo ACL cohort study. J Orthop Sports Phys Ther 44:914–923. http://dx.doi.org/10.2519/jospt.2014.4852
23. Logerstedt D, Grindem H, Lynch A et al (2012) Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. Am J Sports Med 40:2348–2356. http://dx.doi.org/
24. Logerstedt D, Lynch A, Axe MJ, Snyder-Mackler L (2013) Symmetry restoration and functional recovery before and after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 21:859–868. http://dx.doi.org/
25. Lynch AD, Logerstedt DS, Grindem H et al (2013) Consensus criteria for defining 'successful outcome' after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. Br J Sports Med. http://dx.doi.org/
26. Mandelbaum BR, Silvers HJ, Watanabe DS et al (2005) Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med 33:1003–1010. http://dx.doi.org/
27. Muller U, Kruger-Franke M, Schmidt M, Rosemeyer B (2015) Predictive parameters for return to pre-injury level of sport 6 months following anterior cruciate ligament reconstruction surgery. Knee Surg Sports Traumatol Arthrosc 23:3623–3631. http://dx.doi.org/10.1007/s00167-014-3261-5
28. Myer GD, Ford KR, Brent JL, Hewett TE (2012) An integrated approach to change the outcome part II: targeted neuromuscular training techniques to reduce identified ACL injury risk factors. J Strength Cond Res Natl Strength Cond Assoc 26:2272–2292. http://dx.doi.org/
29. Myer GD, Schmitt LC, Brent JL et al (2011) Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. J Orthop Sports Phys Ther 41:377–387. http://dx.doi.org/
30. Neeter C, Gustavsson A, Thomee P, Augustsson J, Thomee R, Karlsson J (2006) Development of a strength test battery for evaluating leg muscle power after anterior cruciate ligament injury and reconstruction. Knee Surg Sports Traumatol Arthrosc 14:571–580. http://dx.doi.org/
31. Noyes FR, Barber SD, Mangine RE (1991) Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. Am J Sports Med 19:513–518. http://dx.doi.org/
32. Paterno MV, Schmitt LC, Ford KR et al (2010) Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. Am J Sports Med 38:1968–1978. http://dx.doi.org/
33. Piva SR, Fitzgerald K, Irrgang JJ et al (2006) Reliability of measures of impairments associated with patellofemoral pain syndrome. BMC Musculoskelet Disord 7:33. http://dx.doi.org/10.1186/1471-2474-7-33
34. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB (2006) Star excursion balance test as a predictor of lower extremity injury in high school basketball players. J Orthop Sports Phys Ther 36:911–919. http://dx.doi.org/
35. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR (2007) Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. Phys Ther 87:337–349. http://dx.doi.org/
36. Risberg MA, Holm I, Myklebust G, Engebretsen L (2007) Neuromuscular training versus strength training during first 6 months after anterior cruciate ligament reconstruction: a randomized clinical trial. Phys Ther 87:737–750. http://dx.doi.org/
37. Roelofs J, Sluiter JK, Frings-Dresen MH et al (2007) Fear of movement and (re)injury in chronic musculoskeletal pain: Evidence for an invariant two-factor model of the Tampa Scale for Kinesiophobia across pain diagnoses and Dutch, Swedish, and Canadian samples. Pain 131:181–190. http://dx.doi.org/10.1016/j.pain.2007.01.008
38. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE (2015) Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. Med Sci Sports Exerc 47:1426–1434. http://dx.doi.org/10.1249/MSS.0000000000000560
39. Schmitt LC, Paterno MV, Hewett TE (2012) The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther 42:750–759. http://dx.doi.org/
40. Sturgill LP, Snyder-Mackler L, Manal TJ, Axe MJ (2009) Interrater reliability of a clinical scale to assess knee joint effusion. J Orthop Sports Phys Ther 39:845–849. http://dx.doi.org/10.2519/jospt.2009.3143
41. Thomee R, Kaplan Y, Kvist J et al (2011) Muscle strength and hop performance criteria prior to return to sports after ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 19:1798–1805. http://dx.doi.org/
42. Thomee R, Neeter C, Gustavsson A et al (2012) Variability in leg muscle power and hop performance after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 20:1143–1151. http://dx.doi.org/
43. Webster KE, Feller JA, Lambros C (2008) Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. Phys Ther Sport 9:9–15. http://dx.doi.org/10.1016/j.ptsp.2007.09.003
44. Woby SR, Roach NK, Urmston M, Watson PJ (2005) Psychometric properties of the TSK-11: a shortened version of the Tampa Scale for Kinesiophobia. Pain 117:137–144. http://dx.doi.org/10.1016/j.pain.2005.05.029

Erratum to: Is Notchplasty Necessary for Anatomic ACL Reconstruction?

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