Knee Arthroscopy

An Up-to-Date Guide

Jin Goo Kim
Editor

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Editor
Jin Goo Kim
Department of Orthopedic
Hanyang University
Myong Ji Hospital
Gyeonggi-do, Korea (Republic of)

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Preface

"The Show Must Go On"

It was when the epic music of the ending credits from the movie *Bohemian Rhapsody, which* stirred our hearts back in early 2019, that Springer suggested that I write a book about knee joint arthroscopy with its most recent update. It was not an easy task, and I knew that it would require a lot of time and effort, but I was grateful and honored to have such an opportunity and started writing after accepting the offer.

Two years from then, a series of unthinkable events occurred.

We've been enduring the long tunnel of the COVID-19 outbreak, the world's most brutal virus in human history, which caused an unprecedented disruption in medical education and the exchange among healthcare professionals.

This left a big impact in the orthopedic surgery area; with the exponential growth in COVID-19 cases, there was a deficiency in the number of medical facilities with such specialty; a reduction in elective surgeries, including knee arthroscopic, due to the lockdowns; and confusion among the doctors not knowing how to handle such situations during the pandemic.

Due to national lockdowns and social distancing, sports events were canceled or postponed. As sports participation in all fields was significantly reduced, sports medicine and knee arthroscopic surgeries also faced a crisis of "temporary lockdown."

As international travels were restricted, many global academic conferences worldwide have been canceled or postponed, which discouraged so many medical professionals and researchers and caused them to lose their zeal in the area.

Despite all this, I'm reminded that the show must go on!!

Knee joints play an essential role in our day-to-day activities as a shock absorber, and arthritis pain remains to be one of the critical problems for all to resolve, which is labeled as the fifth most disruptive pains that affect our quality of life. Despite people's low physical activities due to the pandemic, the number of people with arthritis is still quite significant.

Most knee surgeries aside from artificial joint surgery are now treated with arthroscopy, which has become a standard surgical procedure. Around the world, many diligently find innovative ways of trials and approaches to share, evaluate, and advance.

We have been able to access such systematically studied evidence in our textbooks over the past few decades, which is a result of the long-enduring studies of our researchers.

Through such efforts, new academic foundations and clinical systems are established, but we also need a comprehensive approach of timely introducing new and creative studies.

The title of this book, Knee Arthroscopy: An Up-to-Date Guide, reflects the latter approach.

Although many known or established contents have been omitted, this textbook intends to adequately cover the new diseases, treatments, and trends to be considered amid controversies and changes with an effort to collaborate with the best authors who would best introduce the subject.

I am so honored and grateful to my teachers, lifelong mentors: Professor Jin Hwan Ahn, Freddie Fu, and Christopher Harner for their contribution to this textbook; they have continuously inspired me and shared their knowledge with me.

Unfortunately, in the course of writing this book, we lost a great researcher, Hua Feng. He was also my best friend, who had a brave heart; I have been given the heartbreaking honor to print his chapter, "High Grade Pivot Injuries and Quantitative Evaluations of Degree of Instability". His study will be a useful guide for future generations, and the passion he poured into his research will never be forgotten by his colleagues and students.

In this book, I aim to cover all the necessary details of arthroscopic surgery, especially in introducing novel and experimental efforts with many meniscus problems.

I am grateful to Romain Seil for introducing Korea at various European and international conferences as an exemplary meniscus country, and I'm pleased to present some of his comprehensive meniscus problems in ACL injuries.

In the past few decades, my main concentration has been on meniscus preservation, and I wanted to introduce meniscus root repair and meniscus allograft transplantation as productive investigations. In this process, I would like to thank many friends and colleagues for their dedication to this textbook.

In the end, I believe that these efforts will lead to delay or avoid joint replacement surgery and other concomitant diseases in this aging society. In struggling to put these questions together, I am happy to introduce my trusted old friends, Nobuo Adachi and Hideyuki Koga, who showed such a bold new approach to these concerns.

I have high hopes that these mere concepts being formulated in our minds will be disseminated as a general practice as we collaborate together worldwide.

I wouldn't have finished this book without the efforts of many International and Korean researchers, colleagues who went through the field of knee arthroscopy and sports medicine with me.

I would like to sincerely thank my coworkers, Dr. Dhong Won Lee and research assistant Hye Yun Jung, for their hard work on publishing this book; lastly, my beloved wife Jee Eun Kim and my two sons, June Suk and

Jun Mo, for always trusting in me and being my strongest advocates in this research.

This book will be published in April 2021. I hope that this book will be a line of hope to overcome the past Covid-19 era.

“April is the cruelest month, breeding lilacs out of the dear land,
Mixing memory and desire,
Stirring dull roots with spring rain”
-T. S. Eliot-

Gyeonggi-do, Korea (Republic of) Jin Goo Kim

Contents

Biomechanics of the Knee

Jeong Ku Ha

Abstract

Knee joint is one of the largest and the most complex joints in human body. It is also the most commonly injured joint, because femur and tibia with long lever arm, which consist of knee joint, can cause injury with high energy on the knee joint. Cruciate ligament and/or cartilage injury result in alteration of biomechanics of the knee joint, followed by severe deterioration of the joint. Thus, to understand normal biomechanical characteristics of the joint is essential to know what happened in the injured joint. This also helps in establishing a strategy to operate and propose rehabilitation protocol, and understand effects of various kinds of brace and orthosis.

Keywords

Biomechanics · Mechanical axis · Gait · Anterior cruciate ligament · Anterolateral complex · Posterior cruciate ligament · Posterolateral corner

J. K. Ha (✉)
Department of Orthopedic Surgery, Inje University, Seoul Paik Hospital, Seoul, Republic of Korea
e-mail: revo94@hanmail.net

Alignment

Mechanical axis of the lower limb, which is from the center of hip joint to the center of the ankle joint, passes the center of the knee joint. Anatomical axis of the femur bone forms 6 to 9-degree valgus angle to the mechanical axis and the mechanical axis forms 3-degree valgus angle to the vertical axis of the body. Transverse axis of the knee joint is parallel to the ground, when a human body is on erect position. If there is varus or valgus deformity in the knee joint, body weight distribution shifts medial or lateral compartment which causes a pathologic change in the knee joint (Fig. 1).

Joint Movement

Knee joint is a kind of hinge joint (ginglymus), however, consisting of more complex movement such as rotation than simple flexion–extension movement. The medial femoral condyle is larger than lateral condyle in its anteroposterior length. When lateral compartment of the joint reaches full extended position, medial joint has still more articular surface to move on. Therefore, tibia rotates externally about 15 degrees when it is fully extended. This is called "screw-home" movement.

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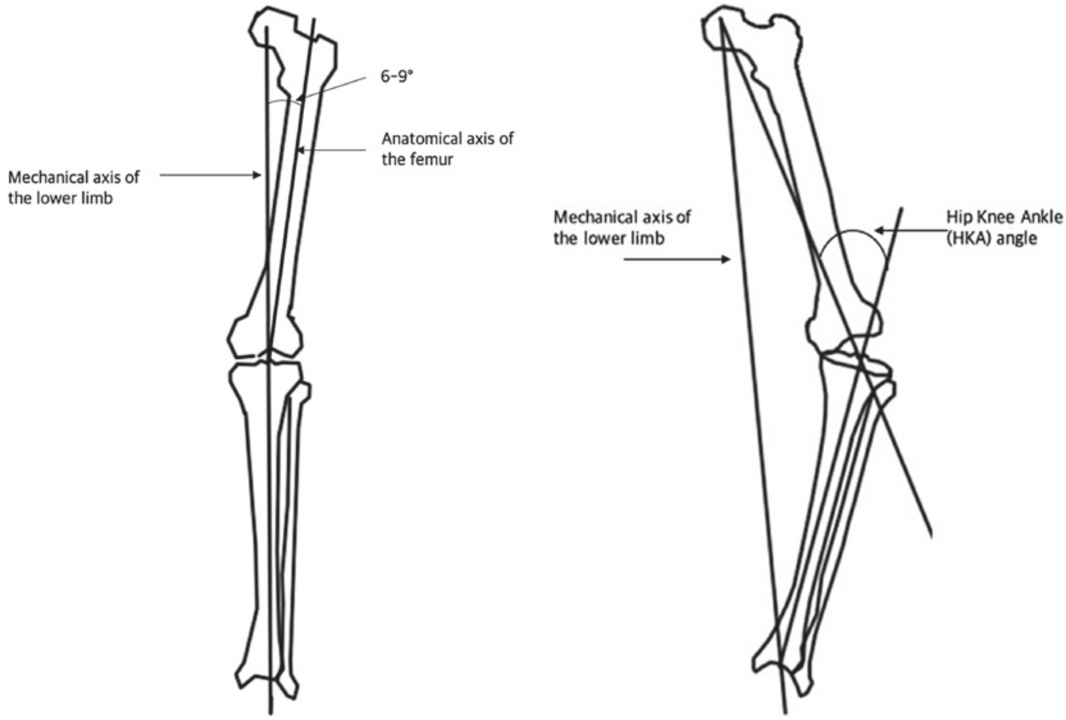

Fig. 1 Mechanical axis of lower extremity. HKA: Hip–knee–ankle angle

Gait

Level Walking

Stance phase (60–62% gait cycle)

- Initial contact: The moment the foot contacts the ground. Weight is rapidly transferred onto the outstretched limb, the first period of double-limb support.
- Midstance: The body progresses over a single, stable limb.
- Terminal stance: Progression over the stance limb continues. The body moves ahead of the limb and weight is transferred onto the forefoot.
- Pre-swing: A rapid unloading of the limb occurs as weight is transferred to the contralateral limb, the second period of double-limb support.

Knee joint is extended at initial contact and flexes until 15 degrees and from midstance knee is fully extended until terminal stance. During pre-swing, knee flexes until 60 degrees for foot clearance in swing (Fig. 2).

Swing phase (38–40% gait cycle)

- Initial swing: The thigh begins to advance as the foot comes up off the floor.
- Mid-swing: The thigh continues to advance as the knee begins to extend, the foot clears the ground.
- Terminal swing: The knee extends, the limb prepares to contact the ground.

Stair Climbing

Stair climbing is a common activity of daily living and the ability to do it efficiently is important to an individual's quality of life. Stair ambulation ROM at the knee requires approximately 10–20 degrees more knee flexion compared to that of level walking and descent requires about 5–10 degrees less ROM than ascent [1]. During stair ascent and stair descent, the lower limbs move in a cyclical pattern similar to that of level walking, and the gait cycle for both tasks divided into two phases: the stance phase and the swing phase.

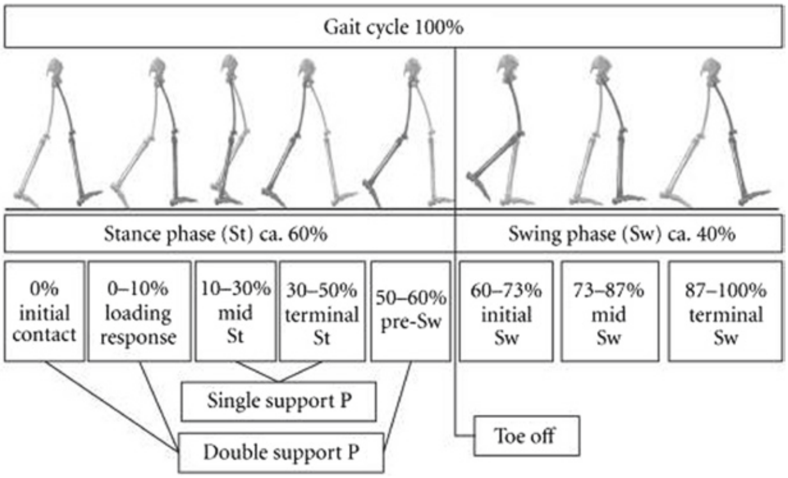

Fig. 2 Normal gait cycle with approximated event timings (Hartmann M, Kreuzpointner F, Haefner R, Michels H, Schwirtz A, Haas JP. Effects of juvenile idiopathic arthritis on kinematics and kinetics of the lower extremities call for consequences in physical activities recommendations. *Int J Pediatr*. 2010;2010:835984. https://doi.org/10.1155/2010/835984)

- Climbing up and down shows different characteristics of time spent in the swing and stance phases: stair ascent (66% stance: 34% swing) and stair descent (60% stance: 40% swing). The stance phase during stair ascent is subdivided into three specific sub-phases: (1) weight acceptance (the initial movement of the body into an optimal position to be pulled up); (2) pull up (the main progression of ascending from one step to the subsequent step); and (3) forward continuance (the complete ascent of a step has occurred and continued progression forward occurs) [2]. The swing phase is subdivided into two specific sub-phases: (1) foot clearance (the bringing of the leg up and over to the next step while keeping the foot clear of the intermediate step) and (2) foot placement (simultaneous lifting of the swing leg and leg positioning for foot placement on step) [2] Figs. (1, 2, 3, 4, and 5). Similar to ascent, the stance phase of descent is divided into three specific sub-phases: (1) weight acceptance; (2) forward continuance (the commencement of single leg support and the body begins to move forward); (3) controlled lowering (the major portion of progression when descending from one step to the next) [2]. The swing phase of descent is subdivided into two specific sub-phases: (1) leg pull through (the swing through of the leg) and (2) preparation for foot placement (FP) (Fig. 3).

ACL

The ACL primarily restricts anterior sliding of the tibia over the femur thereby preventing hyperextension of the knee joint. In terms of biomechanical properties of ACL, the stress–strain plot of ACL obtained under tensile loading shows a triphase graph, consisting of (i) the toe region, (ii) the linear region, and (iii) the yield region (Fig. 4). In the previous literatures, they reported that the ultimate tensile force of ACL varies between 600 and 2300 N [3, 4].

Kinematics and Kinetics of the Knee Joint During Knee Motion

Quadriceps and hamstring is the antagonistic pair of muscles that aids in flexion and extension at the knee joint. Quadriceps contract eccentrically during knee flexion and concentrically during extension. On the other hand, hamstring muscles perform an inverse action. Level walking involves up to 30 flexion at the knee joint, while

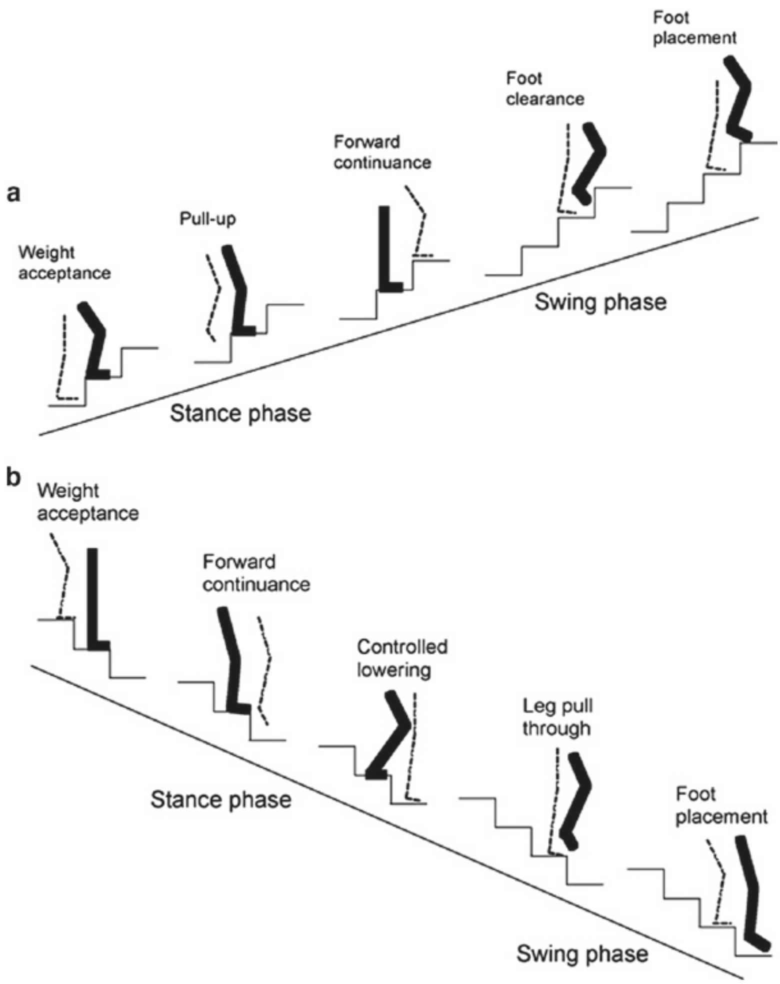

Fig. 3 A schematic of the ascent (**a**) and descent (**b**) cycles of step-over-step stair negotiation

the knee flexion angle varies from 60 to 135 in the case of stair climbing, depending on the height of each stair. For the first 30° of flexion, strain on the ACL is minimal, but between 30° and 135° the larger anterior shear force is applied on the ACL. In addition to the quadriceps and hamstring muscle forces, gastrocnemius muscle forces and ground reaction force act during flexion and extension of the knee joint. The total shear force at the knee joint shall depend on the magnitude and direction of the individual forces. However, the maximum shear force is significantly dependent on the force exerted by the quadriceps muscle via the patellar tendon. These movements are restrained by the ACL.

Markolf et al. reported in their cadaveric study that the highest ACL force of 300 N was observed at hyperextension (−5° of flexion) of the knee. Forces acting on the ACL were evaluated using simulated models during various phases of gait. The gait cycle during level walking is composed of eight phases: (1) initial contact—heel strike, (2) foot flat or loading response, (3) midstance or contralateral toe off, (4) terminal stance-heel off or contralateral heel strike, (5) pre-swing or toe off, (6) initial swing, (7) midswing, and (8) terminal swing [5, 6] (Fig. 5). Morrison et al. reported that the maximum force acting on the ACL was calculated to be 156 N and the ACL was loaded during

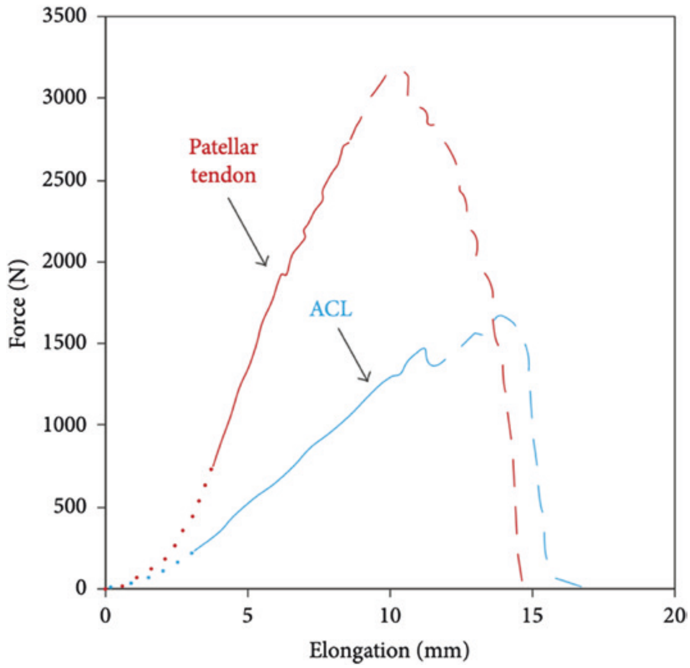

Fig. 4 Tensile strength of ACL and the patella tendon. The dotted lines represent the toe region, continuous lines represent the linear region, and dashed/broken lines represent the yield region (Marieswaran, M., Jain, I., Garg, B., Sharma, V., & Kalyanasundaram, D. (2018). A Review on Biomechanics of Anterior Cruciate Ligament and Materials for Reconstruction. *Appl Bionics Biomech, 2018*, 4657824. https://doi.org/10.1155/2018/4657824)

5–25% of the gait cycle after heel strike [7]. Collins et al. published a study that about 900 N force was estimated to act on the ACL during the early stance phase [8].

Biomechanics of ACL Reconstruction

Tunnel Position

Graft positioning is one of the most important factors in ACL reconstruction, in order to restore the physiologic joint movement, avoid increased anterior displacement and pathologic patterns of knee rotation. If femoral tunnel is created too anteriorly, the graft becomes tight in flexion and slackens in extension, on the contrary if it is too posterior, tight in extension and slacken in flexion. Tibia tunnel placement is also important. Anterior tibia tunnel can result in graft tightness in flexed position, whereas posterior tibia tunnel can result in graft tightness in extended position. Medial or lateral placement of tibia tunnel is related to impingement at ipsilateral femoral condyle [9].

Femoral tunnel position has been known for more importance than tibia tunnel position. The concept of isometry is to avoid changes in graft length and tension during knee flexion and extension to avoid graft failure by overstretching. However, isometric placement of graft will result in a more vertically oriented graft in the sagittal plane and less effective for controlling rotational motion. Furthermore, basic science studies have shown that the normal ACL is not isometric and it is located lower [10]. Several studies reported that anatomical placement of femoral tunnel results in knee kinematics closer to the intact knee than isometric placement [10, 11].

Graft Material

Autograft

Most common choices for autografts are bone–patella tendon–bone (BPTB), hamstring tendon, and quadriceps tendon (bone). All autograft undergo weakening because of tissue necrosis after implantation, so initial strength of the graft should be larger than that of native ACL to make up for the loss during ligamentization process, which persists over a period of 24 months after

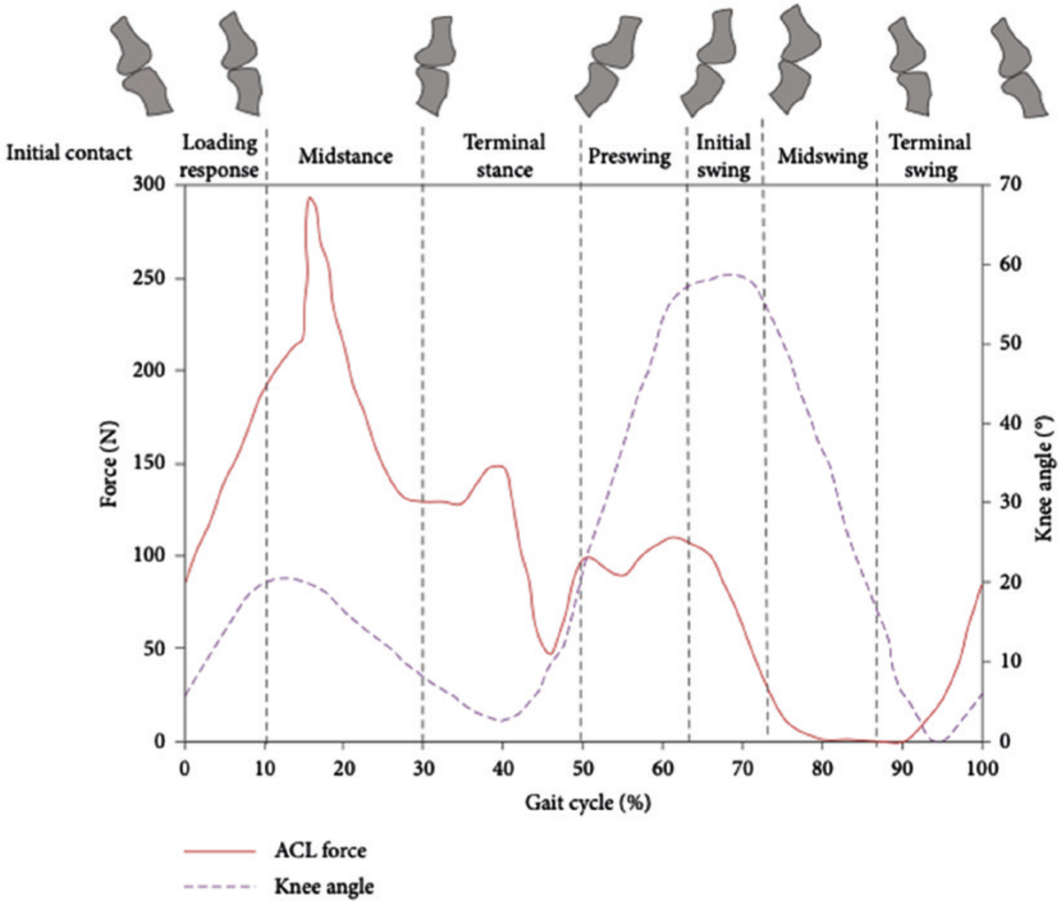

Fig. 5 Forces acting on ACL during a simulated gait cycle along with changes in the knee angle during the gait cycle (Marieswaran, M., Jain, I., Garg, B., Sharma, V., & Kalyanasundaram, D. (2018). A Review on Biomechanics of Anterior Cruciate Ligament and Materials for Reconstruction. *Appl Bionics Biomech, 2018*, 4657824. https://doi.org/10.1155/2018/4657824)

surgery [12]. Intact ACL graft has a 2160 N of ultimate failure load and 242 N/mm of stiffness, whereas quadruple hamstring tendon graft shows 4140 N of ultimate failure load and 807 N/mm of stiffness, quadriceps tendon autograft has 2174 N of ultimate failure load and 463 N/mm of stiffness, and patella tendon–bone graft has 2977 N of ultimate failure load and 455 N/mm of stiffness [3, 13, 14].

Allograft

Allograft-based replacement surgeries require reduced surgery time on the patient and donor site morbidity is eliminated, therefore shorter recovery time is expected in this procedure. Availability of donor, donor medical history, and sterilization processes of allografts affect the quality of the graft. Allografts have a longer incorporation time with subsequent slower rehabilitation and possibility of disease transmission.

Rotational Instability, Anterolateral Complex, and ALL

ACL tears are one of the most common injuries among athletes; however, high rate of graft rupture [15] and low rate of return to pre-injury levels of sport still remain important postoperative issues. Although it is multifactorial, the residual rotational instability is the most important issue to be overcome [16]. Because femoral tunnel position and direction of the graft are considered to have direct relation with rotational stability, there have been numerous attempts to find out proper tunnel position to control rotational instability. However, interests about additional reconstruction procedure at the anterolateral part of the knee joint are getting increased, because provision of an increased lever arm with extra-articular augmentation procedure is more effective to control rotational stability than isolated intra-articular reconstruction.

“Rediscovery” of the anterolateral ligament prompts hot discussion about the anatomy and function of anterolateral structures of the knee joint. Claes et al. reported that a distinct structure of the lateral compartment of the knee is identified and named it “anterolateral ligament”; however, there has been similar observations in the literature. “Pearly fibrous resistant band” by Paul Segond [17], “middle third of the lateral capsular ligament” by Hughston et al. [18], and “anterolateral femorotibial ligament” by Muller [19] might be different descriptions of “ALL.”

Anatomy of Anterolateral Complex

The anterolateral complex is located on the anterior and lateral part of the knee, composed of Superficial IT band and iliopatella band, deep IT band incorporating Kaplan fiber system (two suprocondylar attachments and retrograde attachment continuous with the capsulo-osseous layer of the IT band), ALL, and capsule. The ALL is a capsular structure within Seebacher layer 3 of the anterolateral capsule of the knee [20].

The femoral origin of the ALL is typically found just posterior and proximal to the lateral epicondyle [21]. It runs distally and approaches the joint line. Some fiber of ALL are attached to the lateral meniscus and anterolateral capsule; however, majority of the fibers continues to go distally and inserted at the proximal tibia just behind Gerdy’s tubercle. Tibia attachment is 11.7 mm wide and is centered 21.6 mm posterior to Gerdy’s tubercle, 4–10 mm from the joint line [22, 23].

ALL is non-isometric ligament structure in which the length increases with increase in knee flexion [24]. It shows different elongation patterns between the anterior and posterior borders with a continuous decrease in the percentage elongation of the posterior border as knee flexion increases [25]. Because of this characteristic, it is recommended to fix the graft during ALL reconstruction at the full extension of the knee.

Biomechanics of Anterolateral Complex

Structural property tensile testing of the isolated ALL by Helito et al. shows 204.8 N of ultimate failure load and 41.9 N/mm of stiffness [26]. Another research by Kennedy et al. reported 175 N of ultimate failure load and stiffness 20 N/mm [27]. Consensus is that the ALL has variable gross morphology between individuals in terms of size and thickness [20]. This implies that ALL is not a primary stabilizer of the knee joint due to significantly lower ultimate loads compared with true ligaments found in the knee [28].

Many biomechanics studies have been performed investigating the kinematics of the knee and anterolateral structures. Sectioning of the ALL showed significant increase in anterior translation and internal rotation after the ACL was sectioned during an early phase pivot shift [29]. On the contrary, a study showed that the anterolateral capsule behaves more like a fibrous sheet rather than a distinct ligamentous structure, disputing the existence of a discrete ALL [30]. Consensus was established: the primary soft tissue stabilizer of coupled anterior translation and internal rotation near extension is the ACL. Secondary passive stabilizers include the ITB including the Kaplan fiber system, the lateral meniscus, the ALL, and the anterolateral capsule [20, 29, 31].

In terms of ALC reconstruction, numerous studies showed that an ALL reconstruction is to be of benefit in controlling the pivot shift with its femoral attachment posterior and proximal to the LCL. This point showed minimal length change during the flexion cycle [32–34]. Another study demonstrated that when a combined ACL and anterolateral injury exists, isolated ACL reconstruction fails to restore normal knee kinematics and only combined ACL and lateral extra-articular procedures (ALL reconstruction or lateral tenodesis) were able to restore normal kinematics [35]. However, there is a concern about over-constraints of normal motion of the lateral compartment in lateral extra-articular procedures used as an augmentation to ACL reconstruction [20].

Posterior Cruciate Ligament and Posterolateral Corner

It runs from the lateral surface of the medial femoral condyle to a depression posterior to the intra-articular upper surface of the tibia. Traditionally, it is known to be composed of two bundles, anterolateral and posteromedial bundles. There is an anterior meniscofemoral ligament (ligament of Humphrey) and a posterior meniscofemoral ligament (ligament of Wrisberg) around the PCL.

PCL is a primary restraint to posterior tibial translation throughout knee flexion, especially at high angles of knee flexion (60–120). Many authors have shown increased posterior tibial displacement in PCL-deficient knees throughout the arc of motion. Gollehon et al. reported that isolated section of the posterior cruciate ligament produced a significant increase in posterior translation at all angles of flexion of the knee [36]. Li et al. also showed that PCL had a primary role in posterior stability at all flexion angles except 150° [37]; however, Pearsall et al. showed that the effect of PCL was more pronounced at higher flexion angle translation and a significant effect was found at knee flexion angles of 60° and 90° [38]. Posterolateral corner acts were combined with PCL. PLC is composed of the LCL, popliteofibular ligament, and the popliteal muscle tendon and acts as a primary static stabilizer to resist posterior translation, posterolateral tibial rotation, external rotation, and varus rotation. The PLC structures along with the cruciate ligaments work together to provide static and dynamic stabilities to the lateral knee [39]. It becomes more important in posterior stabilization as the knee goes from flexion to extension and as the knee flexed, PCL becomes the primary posterior stabilizer [36, 40].

Posterolateral instability is defined as a coupled external rotation with posterior translation. PCL acts as a secondary stabilizer to rotational forces when other ligaments are compromised and other ligaments may provide control to rotation when the PCL is deficient [41]. Combined sectioning of the LCL and the posterolateral part of the capsule resulted in more posterolateral instability than did isolated cutting of either structure [42].

Meniscus

Material properties

- Tensile material properties
  Posterior and middle regions of human medial menisci had a higher tensile modulus than the anterior region [43]. They also noted that posterior and middle regions are wider with same circumferential collagen fibers than anterior region. This would increase the ration of collagen fiber to matrix tissue anteriorly and increase stiffness of the anterior tissue.
  For general comparison, Young's modulus for the meniscal tissue is 150 MPa and for the ACL it is approximately 200–300 MPa. The ultimate stress to failure of meniscal tissue is 20 MPa, while that of ligament tissue is typically 50 MPa [44].
- Compressive material properties
- Favenesi et al. and Procto et al. examined the material properties of bovine menisci and found that the water content of the menisci is around 73% [45, 46]. The water content, hydraulic permeability, and compressive modulus were known to vary according to the depth of the sample location (superficial versus deep) and also the location of the sample (anterior versus central versus deep) [45].

Load Transmission

Meniscus is composed of two types of fibers: circumferential and radial fibers. The menisci transfer forces between the femoral and tibial joint surfaces by the development of hoop (circumferential) stresses within the meniscal tissue. These are tensile stresses transferred along the circumferential collagen fibers of the meniscus between insertions. Seedhom showed that on the lateral side the meniscus carries 70% of the load in the lateral compartment, and on the medial meniscus 50% of the load in the medial compartment [47].

Shock Absorption

As axial compressive loading is converted into hoop stresses within the circumferential collagen fibers, energy is absorbed into collagen fibers and further absorbed by the expulsion of the joint fluid (fluid phase of the meniscus) out of the tissue. A study reported that without the menisci, shock absorption within the knee is reduced by approximately 20% [48].

Meniscal Motion

Menisci move as the femur and tibia move, to maintain maximum congruency in incongruent tibio-femoral joint (convex femoral condyle and flat tibia condyle). Menisci move posteriorly as the knee flexes. The anterior horns were more mobile than the posterior horns, and the lateral meniscus to be more mobile than the medial [49].

Joint Stabilization

The medial meniscus is a significant secondary stabilizer to anterior drawer, of particular importance in the ACL-deficient knee. It acts as a "chock block" resisting AP translation of the medial femoral condyle. When comparing between medial and lateral meniscus, there is a smaller increase in anterior laxity associated with removal of the lateral meniscus compared to that seen with the medial meniscus [50].

Cartilage

Articular cartilage is a specialized form of hyaline cartilage with a thickness of 2–4 mm. It is composed of chondrocyte and extracellular matrix (ECM). Chondrocyte accounts for a small amount of cartilage tissue, but the growth, replacement, and maintenance of the ECM are orchestrated by chondrocytes, which are specialized and metabolically active cells. Articular cartilage is avascular, thus chondrocytes must derive nutrition and oxygen from the synovial fluid by diffusion and must meet energy requirements through glycolysis. Chondrocyte synthesizes the two major articular cartilage macromolecules—Type II collagen and aggrecan—and organize the structure of the matrix.

ECM has the capacity to retain high quantities of water due to its abundance of sulfated glycosaminoglycans, which allows movement without friction and counteracting the impact of compression forces applied onto the joint [51]. Water is the major component of the ECM (75% weight) and tissue fluid. Throughout joint movement, water continually moves into and out of the cartilage to aid in distribution of compressive forces and lubrication of the cartilage surface. Collagen accounts for 20% matrix and Type II collagen (90% of the collagen in articular cartilage) provides structural integrity and tensile and shear strength to the articular cartilage. In matrix, proteoglycan (5%) and non-collagenous proteins and glycoproteins (1%) also exist.

The coefficient of friction estimated at 0.002 in synovial joints allows the tissue to withstand millions of cycles of loading each year without degeneration. Biomechanical properties of native articular cartilage are as follows: ultimate tensile stress—15–35 MPa, compressive modulus—5.5–11.8 MPa, and equilibrium shear modulus—0.05–0.25 MPa [52]. Static compression even within the physiologic range inhibits matrix synthesis; on the contrary, dynamic loading increases synthesis of collagen Type II and aggrecan and increases expression of tissue inhibitors of metalloproteinases (TIMPs).

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Understanding the Complex Anatomy of the Knee

Dhong Won Lee and Min Seok Chang

Abstract

Medial and lateral compartments of the knee joint have complex structures. The medial knee compartment is more stable than lateral compartment due to the sound structures between femur and tibia. The interval concept is more useful for lateral complex approach than the layered anatomic description, because the major lateral structures are concentrated in the layer 3. Treatment of complex structures depends on which structures are injured and successful reconstruction requires a thorough understanding of anatomy and biomechanics. The purpose of this chapter is to review the current concepts of complex anatomy reported in the literature.

Keywords

Knee · Ligaments · Posterolateral corner · Anterolateral complex · Medial collateral ligament · Posteromedial complex · Anatomy · Function · Anatomic reconstruction

D. W. Lee (✉) · M. S. Chang
Department of Orthopaedic Surgery, Konkuk University Medical Center, Konkuk University School of Medicine, Seoul, Republic of Korea
e-mail: osdoctorknee@kuh.ac.kr

M. S. Chang
e-mail: 20140081@kuh.ac.kr

Introduction

The knee joint consists of the medial compartment, the lateral compartment, and the patellofemoral compartment. Various ligaments or complex structures provide stability in all directions to these compartments. Treatment of knee injuries depends on which structures are injured and the severity of instability, and requires a thorough understanding of anatomy and biomechanics to restore native kinematics of the knee joint. Anatomy is the basis for function and surgical reconstruction of injured structures and in its best is applied anatomy. The authors of this chapter are trying to respect, understand, and restore anatomy as close as possible [1]. The purpose of this chapter is to review clinically relevant anatomy and biomechanics to reach successful anatomical reconstruction.

Medial Complex

Layer 1

The first layer to be encountered in the skin incision is the sartorius fascia which is attached to the superior medial surface of the tibia. It forms pes anserinus while wrapping it over semitendinosus and gracilis. The sartorius fascia extends to posterior and covers the medial head of the gastrocnemius and part of the popliteus.

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Semitendinosus and gracilis, which form pes anserinus, are located between the first layer (including sartorius fascia) and the second layer (including superficial medical collateral ligament), with gracilis in the proximal part of the tibial tuberosity. When superficial medial collateral ligament (sMCL) needs to be confirmed and protected, a small incision is made along the proximal of the sartorius and the pes anserinus is elevated, after which the ligament structure that goes down to the tibial attachment at approximately 90-degree angles to the pes anserinus can be identified.

When harvesting the autologous hamstring tendons, semitendinosus tendon and gracilis tendon should be distinguished from each other. They are merged into the pes anserinus insertion (about 19 mm distal and 22.5 mm medial to the apex of the tibial tuberosity), and it is difficult to separate the two tendons at the insertion [2, 3]. However, the semitendinosus tendon is located deeply in the proximal area by the medial femoral crus, and the layer of the semitendinosus tendon and that of gracilis tendon are easily divided proximally (Fig. 1).

There are various accessory tendons (or the fascial bands) between semitendinosus tendon, gracilis tendon, and medial gastrocnemius. The Ýlargest accessory tendon is the fascial band that attaches from the semitendinosus tendon to the gastrocnemius. It is located about 6 to 8 cm (rarely more than 10 cm) above the tibial insertion of the semitendinosus tendon and is about 2.6 cm in length (Fig. 2) [4]. If you do not remove the accessory tendon during hamstring tendon harvesting, the tendon stripper will damage or cut the semitendinosus tendon that you cannot obtain a sufficient length of autologous tendon. Anatomical studies on accessory tendon of hamstring concluded that semitendinosus tendons have almost one or two solid accessory tendons, whereas more than 25% of gracilis tendons do not have accessory tendons. If an accessory tendon cannot be identified during

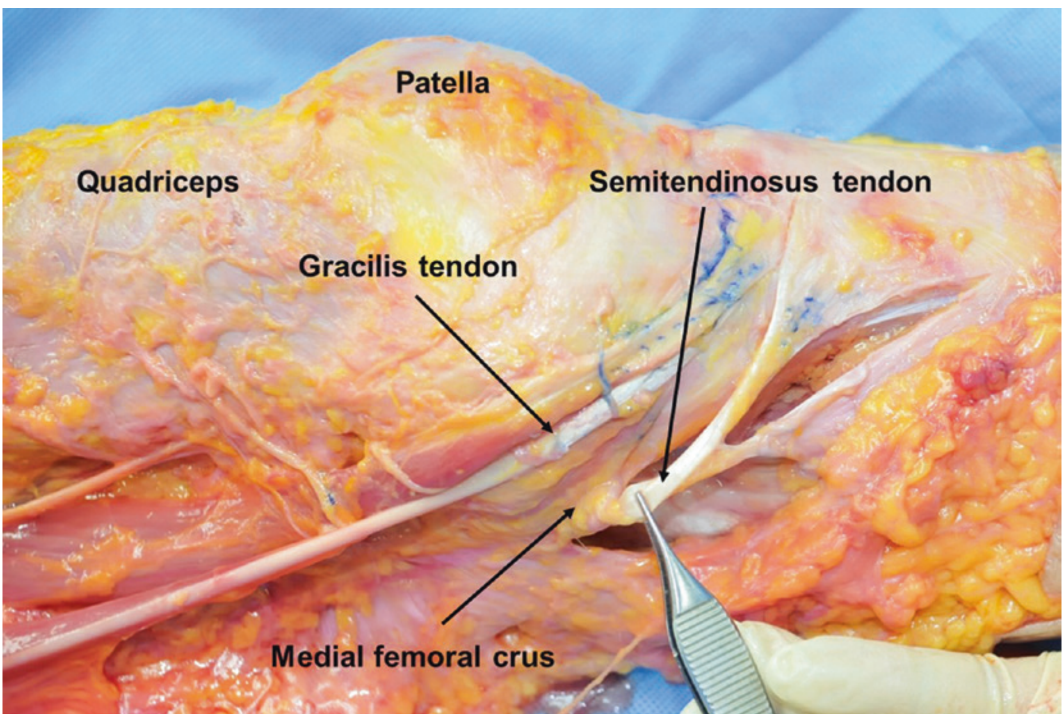

Fig. 1 The semitendinosus tendon is located deeply in the proximal area by the medial femoral crus, and it is easily separated form the gracilis tendon

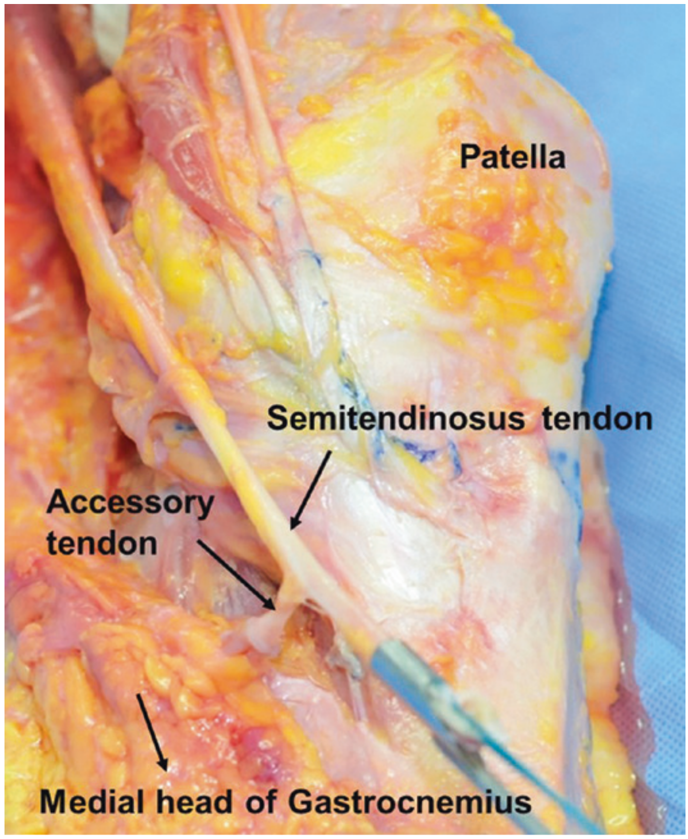

Fig. 2 There are various accessory tendons between semitendinosus tendon, gracilis tendon, and medial gastrocnemius. The largest accessory tendon is the fascial band that attaches from the semitendinosus tendon to medial head of gastrocnemius

hamstring harvesting, you should think about whether the tendon being harvested is a gracilis tendon, not semitendinosus tendon. Hence, the relative position between the two tendons should be verified where the medial crus is located. The saphenous nerve is a branch of the femoral nerve that penetrates between the gastrocnemius and the sartorius of the thigh and superficial to give 4 to 5 branches at 10 to 15 cm above the knee joint. The saphenous nerve is divided into an infrapatellar branch and a sartorial branch when it passes through the adductor canal. The infrapatellar branch usually passes between the inferior pole of the patella and the tibial tuberosity, usually under the sartorius, and therefore it can be injured during autologous hamstring tendon harvesting or proximal tibial osteotomy. Caution is required since this peripheral nerve injury leads to a wide range of sensory deficit of the patellar tendon area, and lateral or medial side of the lower leg. Regarding a sartorial branch, it can be injured during knee arthroscopy when the posteromedial portal is created and medial meniscal repair when posteromedial incision is applied (Fig. 3). The sartorial branch becomes closer to knee joint when the knee is flexed and away from the knee joint during extension. Therefore, it is recommended that the knee extension position be placed to reduce nerve injury during medial meniscus repair.

Layer 2

Clinically important medial structures of the knee are sMCL, deep medial collateral ligament (dMCL), and posterior oblique ligament (POL) [5–8]. These structures allow the medial knee compartment to be more stable than lateral compartment, and this contributes to the fact that the axis of rotation is based in the medial knee compartment [9]. The sMCL is a structure belonging

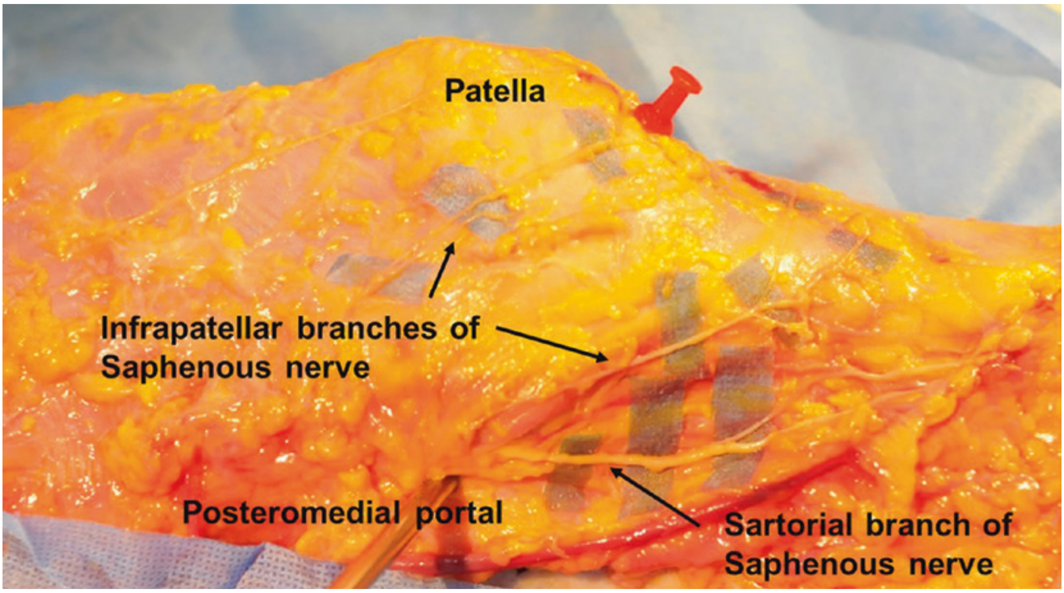

Fig. 3 A sartorial branch of the saphenous nerve can be injured during knee arthroscopy when the posteromedial portal is created

to layer 2 and has one femoral attachment and two tibial attachments. The femoral attachment is 3.2 mm proximal and 4.8 mm posterior to the medial femoral epicondyle. The sMCL is connected to the soft tissue distally and the proximal tibial attachment in 12 mm distal to the tibial joint line over the anterior part of semimembranosus. The distal tibial attachment of sMCL is distal to the tibial joint line in 61 mm [10, 11]. The sMCL provides resistance to external rotation at 30° of flexion and internal rotation (along with the POL) at all flexion angles in addition to being the primary restraint against valgus stress [11].

If the release of sMCL is performed under full understanding of these anatomical characteristics, clinicians can do safe decompression of tightened medial compartment to gain sufficient working field during medial meniscal root repair or medial meniscal allograft transplantation without residual valgus instability [12]. We usually perform selective distal sMCL release via distal subperiosteal stripping while preserving the proximal attachment of sMCL and dMCL, and this technique has been proven in terms of safety and efficacy biomechanically [12]. We suggest that the pie crusting release using a needle is more careful method because it has a limitation in releasing the distal part of the sMCL in a stepwise fashion. Additional iatrogenic injury should be avoided when releasing the distal part of the sMCL, as excessive valgus load during surgery may cause further injury to the medial collateral ligament.

The medial patellofemoral ligament (MPFL) is located in layer 2, which is the same layer as the sMCL. The MPFL originates at "saddle region," which is located between adductor tubercle and medical femoral epicondyle, and it forms a fan-shaped thin structure facing the superior medial patella. It is easily distinguished from the medial retinaculum (Fig. 4). The patellar insertion is superficial and is connected to the patellar periosteum, and there is no deep insertion. According to previous cadaveric study reported by Lee and colleagues, the patellar insertion of the MPFL was 14.2 mm (10–20 mm) below the patella superior pole and 18.6 mm (14.7–21 mm) above the patella inferior pole, and the mean width of the patellar insertion was 14.2 mm (10–15 mm) [13]. They showed that the MPFL and vastus medialis

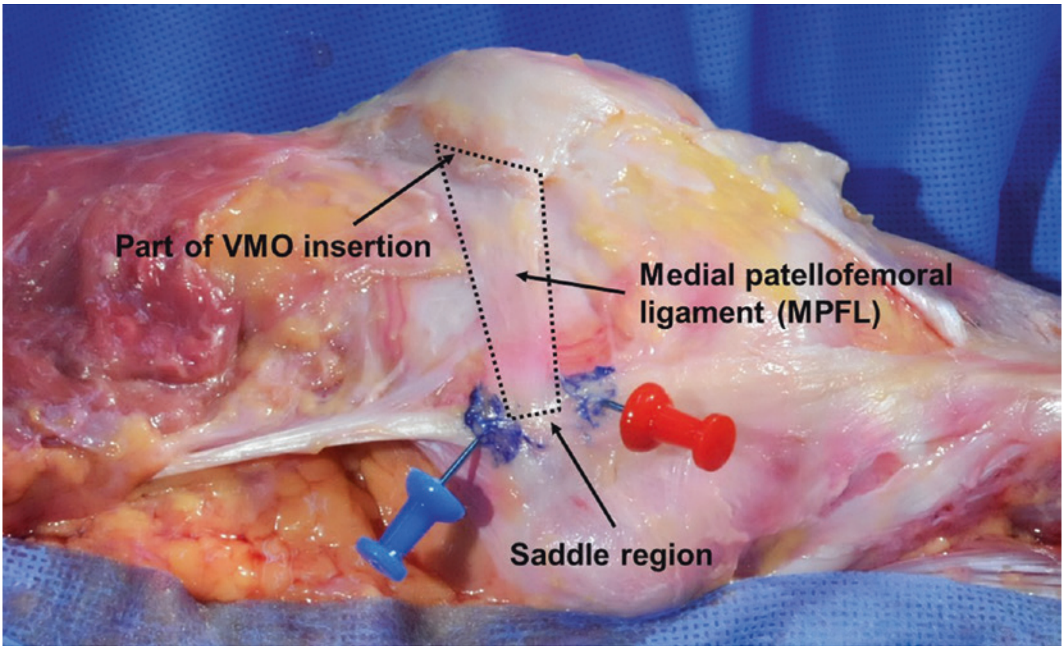

Fig. 4 The medial patellofemoral ligament (MPFL) originates at "saddle region," which is located in between adductor tubercle (blue pin) and medical femoral epicondyle (red pin). The MPFL forms a fan-shaped thin structure facing the superior medial patella. It shares the part of vastus medialis obliquus (VMO) insertion

obliquus (VMO) are connected by patellar insertion and average width of overlapping area was 22 mm (18.8–24 mm). In their study, the femoral origin located at "saddle region" is connected to the sMCL with an average width of the origin of 11.5 mm (10–12.3 mm). In recent literature concerning the anatomy of medial stabilizers of the patella reviewed by Tanaka and colleagues, they highlighted that the proximal patellar insertion of MPFL is divided into MPFL and medial quadriceps tendon femoral ligament (MQTFL) which function primarily in greater degrees of flexion, and these medial patellar stabilizers form a broader complex than previous studies [14]. The tension of MPFL increases at the first flexion 30 degrees and decreases sharply as degrees of flexion increases (Fig. 5).

Based on these anatomical and biomechanical studies, we have performed anatomic medial patellofemoral complex reconstruction using double bundle reconstruction with hamstring tendon autografts and soft tissue fixation using a suture anchor at patellar insertion instead of patellar bone tunnel fixation [13, 15–17]. By repairing superior MPFL graft with VMO, we can preserve dynamic function of the MPFL and make complex structures (Fig. 6). We are setting up a rehabilitation program based on anatomical studies. In the first 3 weeks after MPFL reconstruction, the angle of flexion begins at 30 degrees and gradually increases, but limits the angle of 30 degrees to 0 degrees based on cadaveric study which showed that the tension of MPFL increased at the first flexion 30 degrees.

Layer 3

The dMCL, POL, meniscofemoral ligament, meniscotibial ligament, coronary ligament, and joint capsule belong to layer 3. The posteromedial complex has five major components: the POL, the semimembranosus tendon with its expansions, the oblique popliteal ligament, the posteromedial capsule, and the medial meniscal posterior horn [6].

The dMCL has two areas attached to the medial meniscus including the meniscofemoral

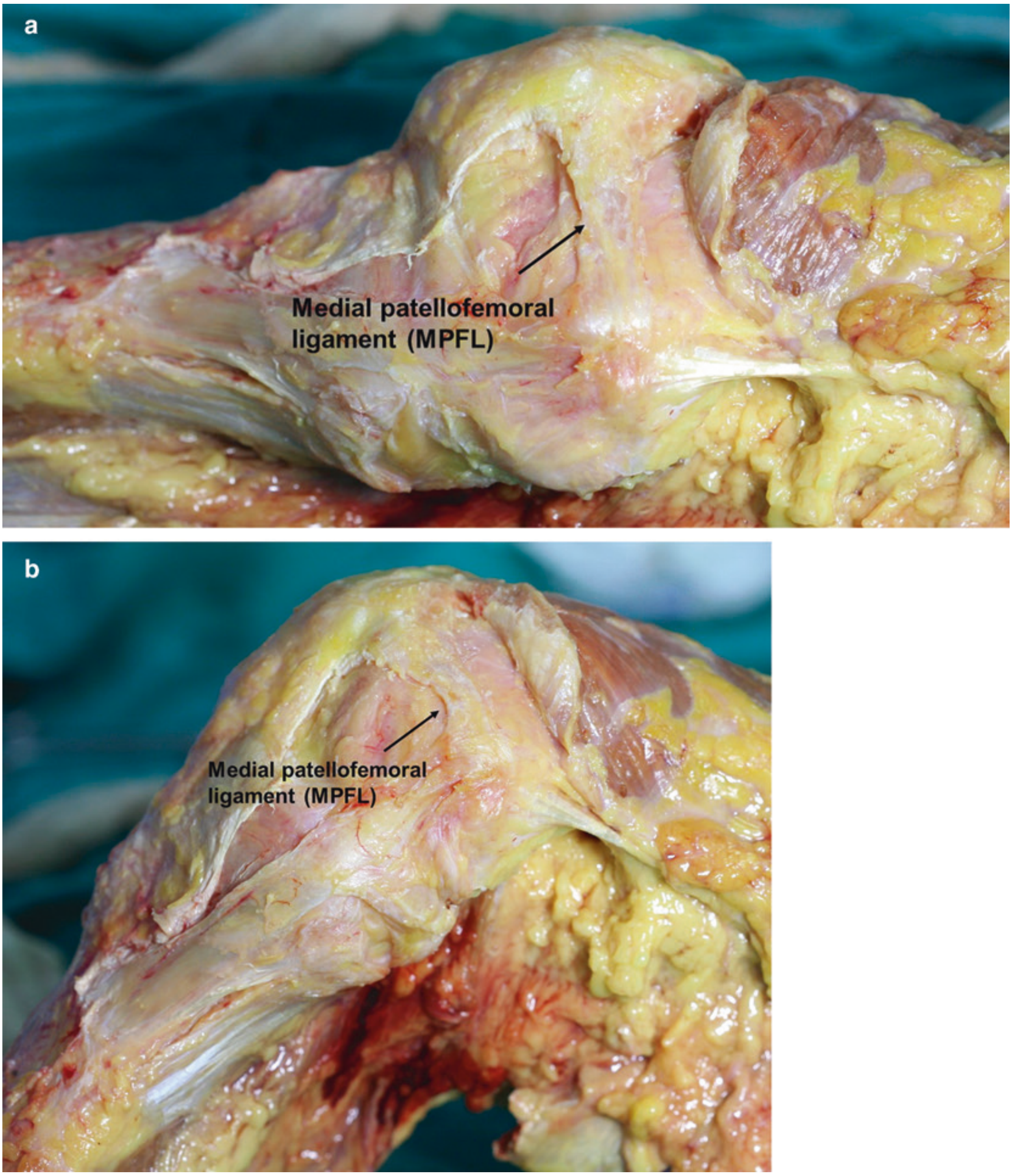

Fig. 5 A tension of medial patellofemoral ligament (MPFL) increases at early flexion angles (**a**) and is slack sharply as flexion angles increases (**b**)

ligament and the meniscotibial ligament, and it seems like that the medial joint capsule is reinforced and thickened. The posterior area of dMCL blends with and becomes inseparable from the central arm of the POL.

The POL has three identifiable arms: the superficial, central, and capsular arms [6]. The POL is attached to the 1.4 mm distal and 2.9 mm anterior in the gastrocnemius tubercle of the tibia, originating 7.7 mm distal and 6.4 mm posterior in the adductor tubercle of the femur, and it is sometimes not be recognized as a definite ligamentous structure (Fig. 7) [10]. The distal attachment of the POL is adjacent to the

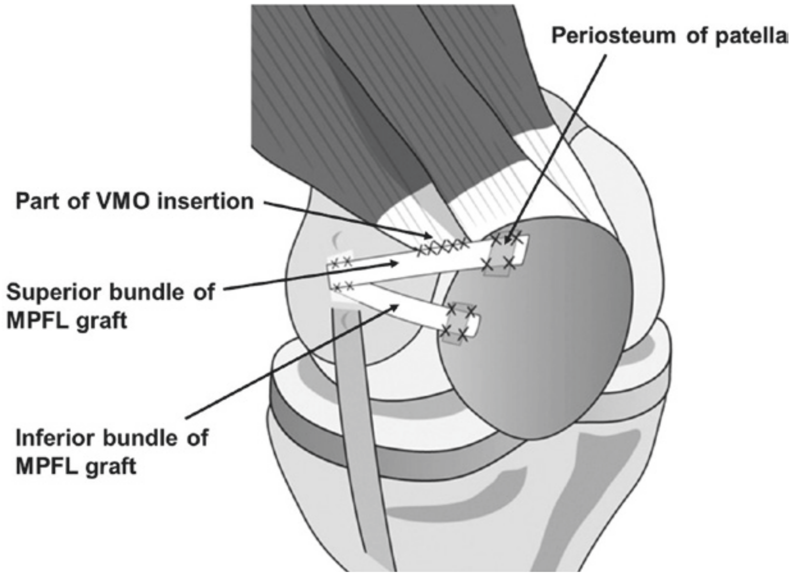

Fig. 6 Anatomic medial patellofemoral complex reconstruction is performed using double bundle graft and soft tissue fixation at patellar insertion. By repairing superior patellar graft with vastus medialis obliquus (VMO), a dynamic function of the medial patellofemoral ligament (MPFL) can be restored

anterior and direct arms of semimembranosus and has an additional attachment to the medial meniscus [11]. The POL provides stabilization in tibial internal rotation during extension as the posteromedial complex is strengthened and thickened [5, 7, 18]. Lee and Kim [19] showed that anatomic reconstruction of triangular medial complex consisting of two main structures including sMCL and POL achieved satisfactory functional outcomes at mid-term follow-up in cases with serious valgus and rotatory laxity (Fig. 8 Permission). They sutured the distal portion of the POL graft with the MCL graft along the anterior arm of the semimembranosus tendon to create a triangular-shaped complex.

Semimembranosus, located between layer 2 and layer 3, is an important dynamic stabilizer of the posteromedial complex [6, 20]. The distal insertion consists of five parts as follows. First, it (pars reflexa or anterior arm) is attached to the periosteum of the anteromedial side of tibia. Second, it (direct arm) is inserted at the tubercle of the posteromedial side of medial tibial condyle below the joint line. Third, it is connected to the oblique popliteal ligament and plays an important role in the posterior stability of the knee. Fourth, it is attached to the medial meniscal posterior horn and posteromedial joint capsule and pulls the meniscus during the knee flexion as contracture of semimembranosus (Fig. 9). DePhillipo and colleagues showed that 86% of 14 fresh-frozen cadavers had the semimembranosus muscle–tendon complex with a firm attachment to the medial meniscal posterior horn, and they suggested that this attachment may have a dynamic role in posteromedial complex and medial meniscal stability [21]. Vieira and colleagues reported that tensioning effect on the POL of semimembranosus is likely to be part of ramp lesion [22]. In this sense, we limit the active leg curl exercise at the initial stage of rehabilitation after medial meniscal posterior horn repair or meniscal allograft transplantation to prevent posterior displacement of the medial meniscus or meniscal allograft due to the contraction of semimembranosus, which causes a shearing force on the repair site. Fifth, it is popliteus aponeurosis expansion.

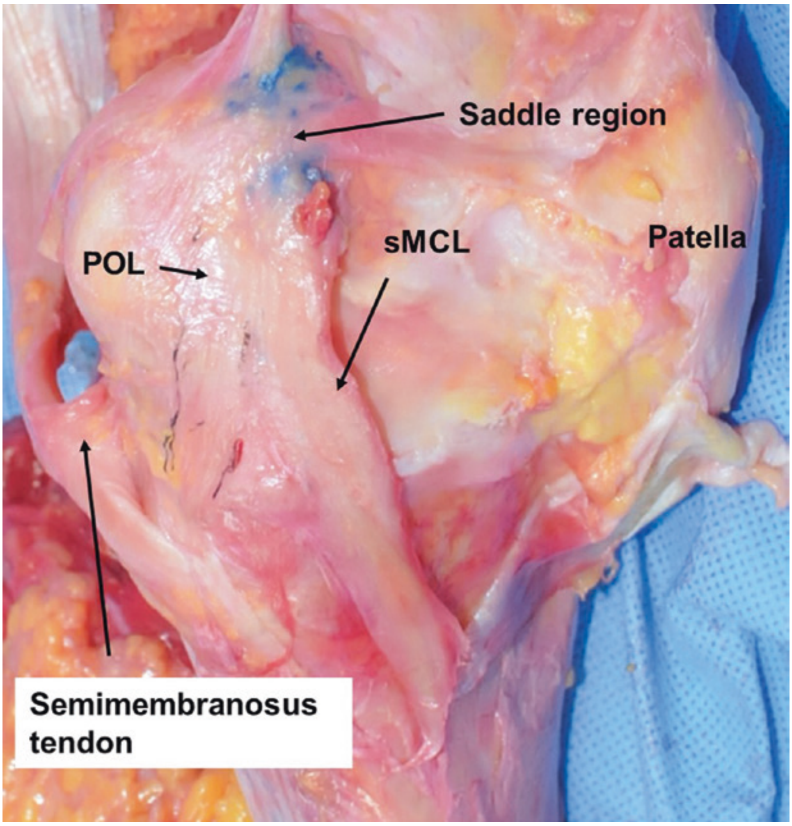

Fig. 7 The posterior oblique ligament (POL) behind the superficial medial collateral ligament (sMCL) is attached at the gastrocnemius tubercle of the tibia, originating distal and posterior in the adductor tubercle of the femur. The distal attachment of the POL is adjacent to the anterior and direct arms of semimembranosus and has a supplemental attachment to the medial meniscus

Lateral Complex

Interval Concept

The interval concept uses three fascia incisions: (1) between the iliotibial band, (2) between iliotibial band and biceps femoris short head, and (3) the inferior fascia of the biceps femoris long head parallel to the peroneal nerve (Fig. 10) [23]. The interval concept is more useful for lateral complex approach than the layered anatomic description, because the major lateral structures are concentrated in the layer 3 classified by Seebacher and colleagues [24].

Interval 1: It is reached by incising the iliotibial band at the site where the lateral femoral epicondyle is palpated. The origin of the popliteus tendon and the lateral femoral epicondyle is identified easily (Fig. 11).

Interval 2: This is the interval between the iliotibial band and the biceps femoris. The popliteus tendon and posterolateral capsule can be identified via posterior traction of the femoral attachment of the lateral head of gastrocnemius (Fig. 12). Clinicians should be familiar with this interval approach as the basis for lateral meniscal repair, lateral meniscal allograft transplantation, and posterolateral complex reconstruction.

Interval 3: It is posterior to the biceps femoris, and delicate thin membrane incision after anterior traction of the biceps femoris can expose the peroneal nerve safely (Fig. 10).

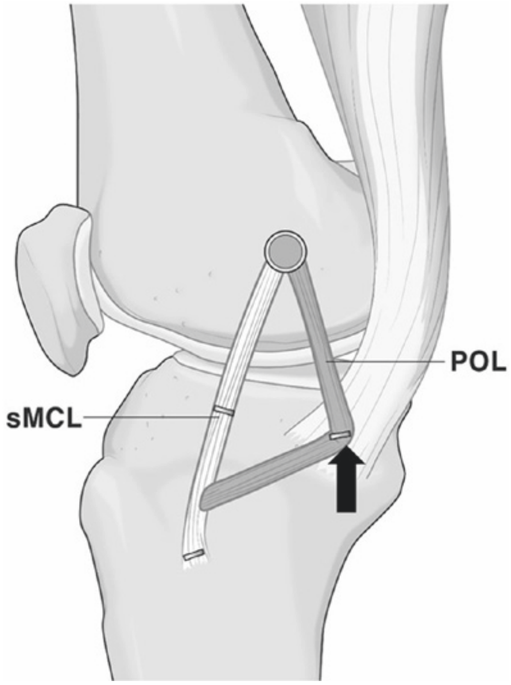

Fig. 8 Anatomic medial complex reconstruction consisting of two main structures including the superficial medial collateral ligament (sMCL) and the posterior oblique ligament (POL) forms triangular complex. Black arrow indicated the semimembranosus tendon (From Dhong Won Lee and Jin Goo Kim. Anatomic medial complex reconstruction in serious medial knee instability results in excellent mid-term outcomes. Knee Surg Sports Traumatol Arthrosc. 2020;28(3):725–32. Reprinted with permission.)

Layered Concept

Layer 1

Iliotibial band (ITB) and biceps femoris tendon are located here. The iliotibial band is inserted into Gerdy's tubercle via the lateral side of the lateral femoral condyle from proximal origin. It is connected to vastus lateralis in the anterior direction and biceps femoris in the posterior direction, and functions as anterolateral stabilizer of the knee joint. When the knee is extended, it moves to the anterior of the lateral femoral condyle and moves to the posterior of the lateral femoral condyle during flexion. The Kaplan fibers, which connect the ITB with the distal lateral femoral condyle, play a dynamic ligamentous junction. Recent review by anterolateral complex (ALC) consensus group meeting reported that the ALC consists of the superficial and deep aspects of the ITB with its Kaplan fibers connected to the distal femur, along with the anterolateral ligament (ALL), and concluded that ALC provides anterolateral rotatory stability as a secondary stabilizer to ACL [25].

Biceps femoris plays an opposite role to pes anserinus (semitendinosus and gracilis) and attaches to fibular head, lateral tibial condyle, and posterolateral capsule. Since the common peroneal nerve passes the posteroinferior part of biceps femoris and runs around the fibular neck, care should be taken not to injure the peroneal nerve during lateral approach. The peroneal nerve is close to the knee joint during extension and is displaced up to a maximum of 2 cm with fibular inferiority during flexion, and it is safe to perform lateral meniscal repair or lateral meniscal allograft transplantation with the knee flexion at 90-degree flexion.

Layer 2

Quadriceps femoris retinaculum, lateral patellofemoral ligament, and patella-meniscal ligament are here. The patellofemoral ligaments consist of superficial oblique retinaculum and deep transverse retinaculum, and transverse patellofemoral ligament of the deep transverse retinaculum contributes to the superolateral stabilization of the patella.

Layer 3

In contrast to the medial knee compartment, the lateral compartment can be called the mobile knee complex. The lateral knee compartment has no distinct ligament which directly connects the tibia and the femur, and this implies much length change during extension–flexion and external–internal rotation at lateral compartment [9].

The posterolateral complex has five major components: lateral collateral ligament (LCL), popliteus tendon, popliteofibular ligament (PFL), lateral head of the gastrocnemius, and fabellofibular ligament. There are

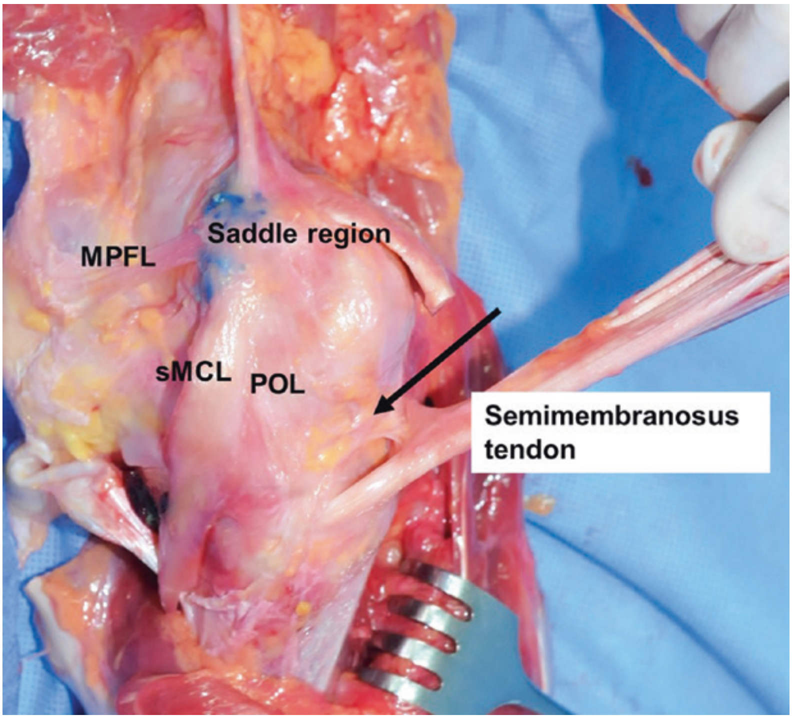

Fig. 9 Semimembranosus has attachments (black arrow) to the medial meniscal posterior horn and posteromedial joint capsule, and they pull the meniscus during the knee flexion as progressive contracture of semimembranosus. MPFL: medial patellofemoral ligament; sMCL: superficial medial collateral ligament; POL: posterior oblique ligament

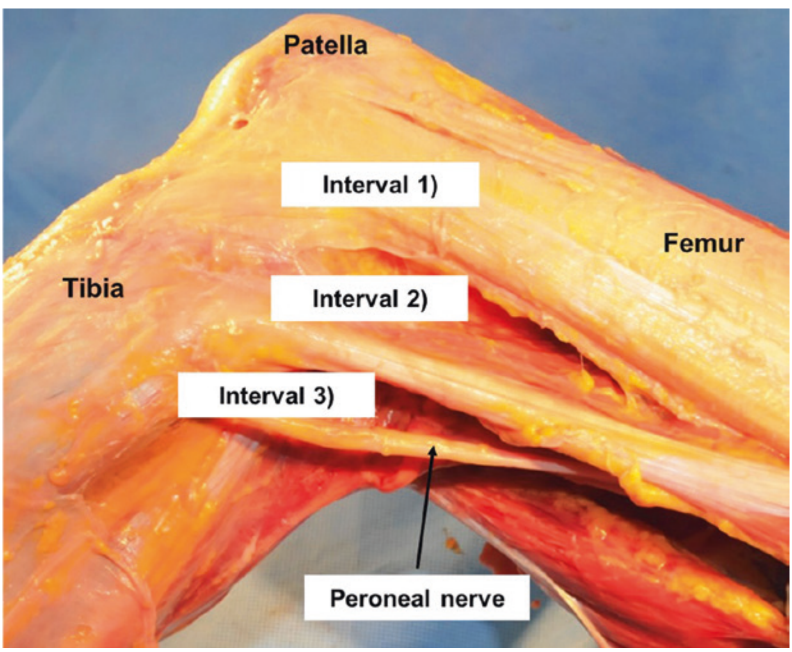

Fig. 10 The interval description for lateral side of the knee has three fascia incisions: (1) between the iliotibial band, (2) between iliotibial band and biceps femoris short head, and (3) the inferior fascia of the biceps femoris long head parallel to the peroneal nerve

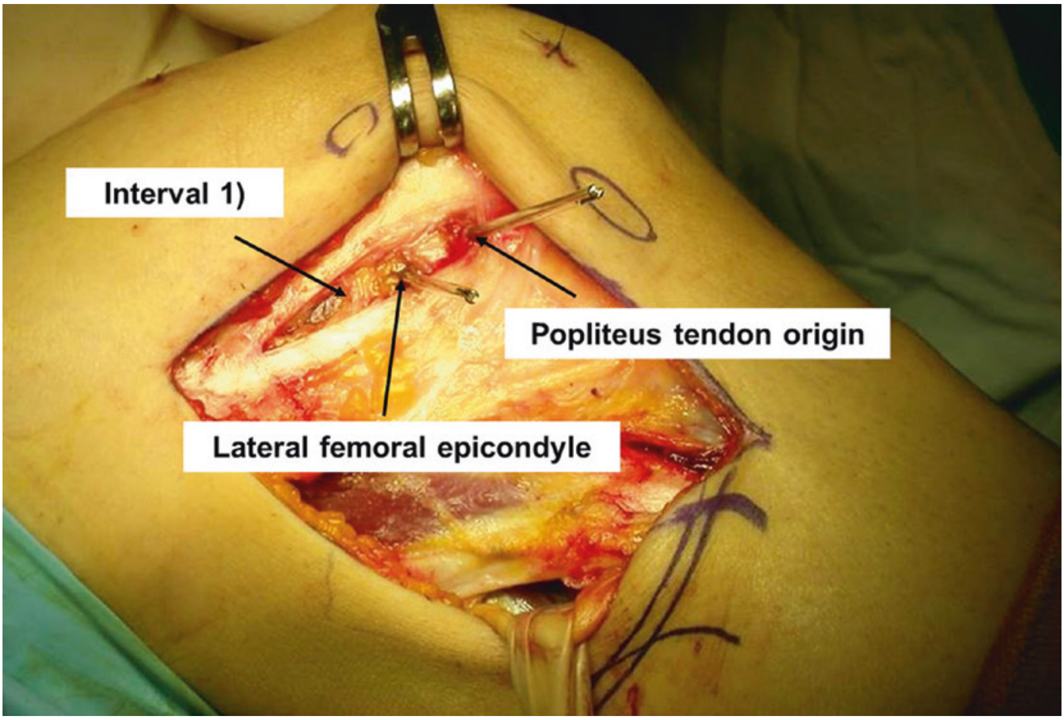

Fig. 11 Interval 1 is reached by incising the iliotibial band at the site where the lateral femoral epicondyle is palpated. The popliteus tendon which passes to anterior of lateral femoral epicondyle is easily palpated and the groove for the popliteus tendon is its origin

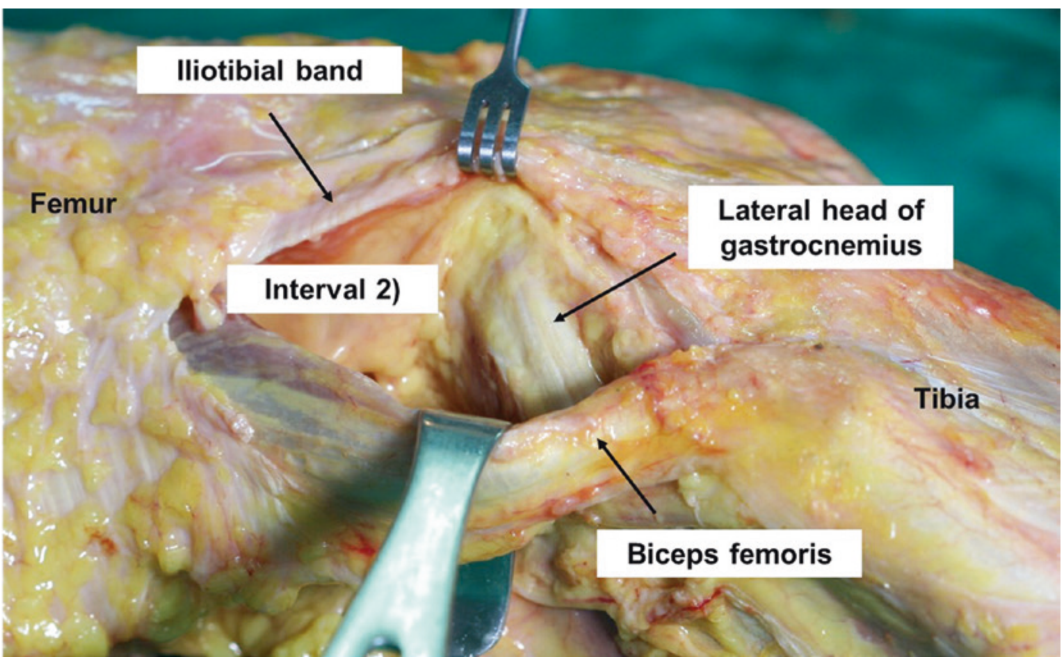

Fig. 12 Interval 2 is the space between the iliotibial band and the biceps femoris. The popliteus tendon and posterolateral capsule can be identified via posterior traction of the femoral attachment of the lateral head of gastrocnemius

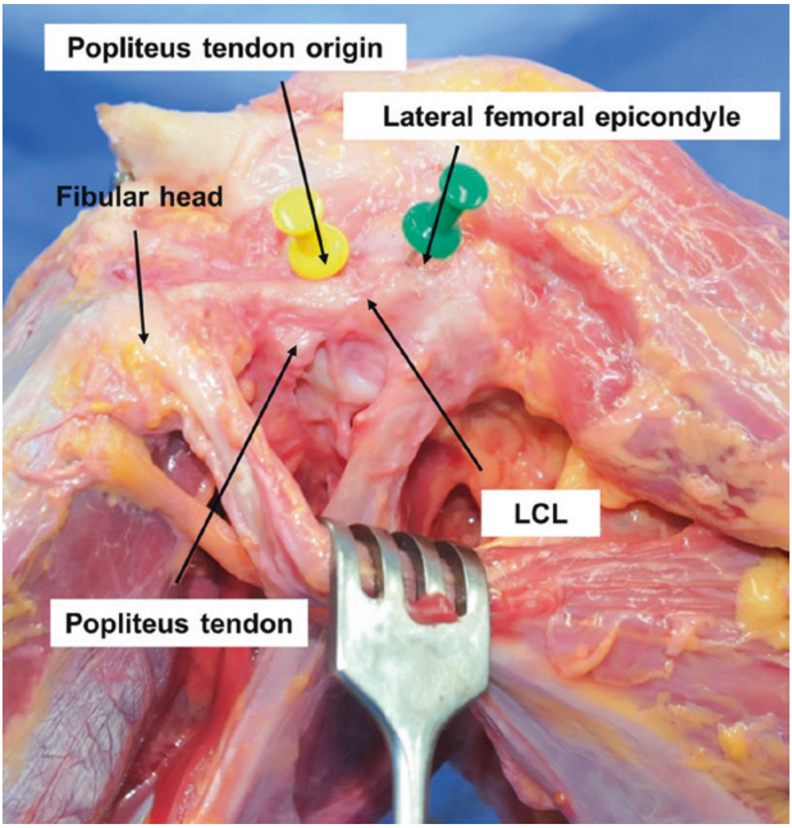

Fig. 13 The femoral origin of popliteus tendon is anterior and distal to the origin of the lateral collateral ligament (LCL) about 18.5 mm diagonally. The yellow pin indicates the popliteus origin and the green pin represents the lateral femoral epicondyle

many variations in these complex structures. Significant structures of anatomical posterolateral complex reconstruction are LCL, popliteus tendon and PFL. The LCL is the primary varus stabilizer at 0° and 30°, and it also provides stability against external rotation and internal rotation of tibia. The origin of the LCL is located 1.4 mm proximal and 3.1 mm posterior to the lateral femoral epicondyle and is attached to the lateral aspect of the fibular head with supplemental fibers extending into the peroneus longus fascia [26]. The popliteus tendon emerges from the popliteus muscle which has insertion at posteromedial side of the proximal tibia and becomes intra-articular structure through the popliteal hiatus. Then, it courses deep to the LCL and attaches to the lateral femoral condyle. The femoral origin of popliteus tendon is anterior and distal to the origin of the LCL about 18.5 mm diagonally (Fig. 13). During posterolateral corner reconstruction, the popliteus tendon passing forward the lateral femoral epicondyle can be easily palpated after confirmation of lateral femoral epicondyle, and then the origin of the popliteus tendon is identified. The function of popliteus tendon is the primary tibial external rotation stabilizer, and it also provides resistance against tibial internal rotation, knee varus, and tibial anterior translation [11]. The PFL originated at the musculotendinous junction of popliteus and is inserted distal to the fibular styloid process. The PFL is divided into an anterior and posterior division, and anterior division is extended with joint capsule and is attached 2.8 mm distal to the tip of the fibular styloid process, whereas the posterior division

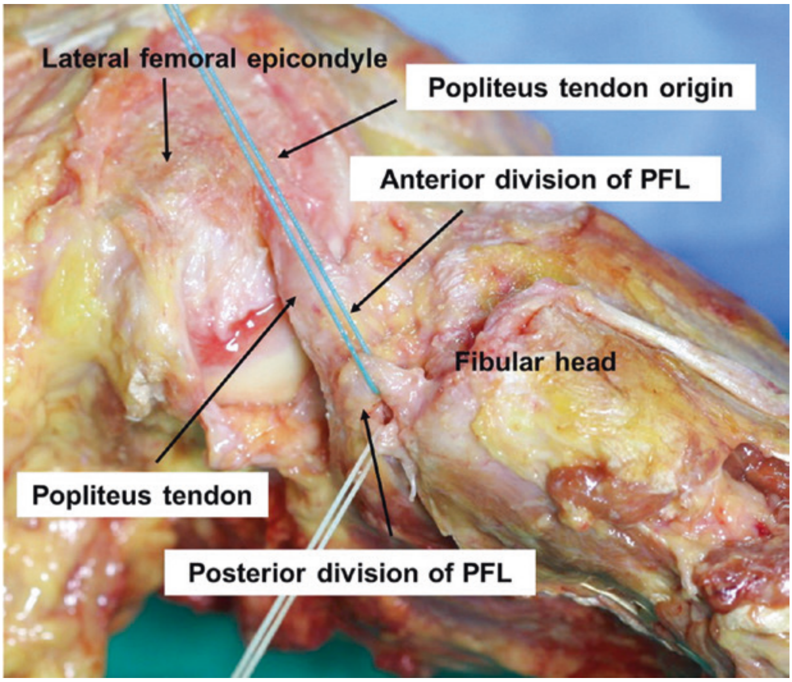

Fig. 14 The popliteofibular ligament (PFL) is divided into an anterior and posterior division, and anterior division is extended with joint capsule

is attached 1.6 mm distal to the tip of the fibular styloid process (Fig. 14) [10, 26]. The PFL provides resistance against tibial external rotation and varus stress. Injury of the PFL can be identified through arthroscopic approach and anterior fascicle can be observed through arthroscopic approach at popliteal hiatus, especially anterior division. The tension of anterior division of the PFL can be checked using probe inserted via the superolateral portal after inserting the 18G needle into the fibular styloid process while observing the popliteal hiatus [27–29]. In addition, arthroscopic approach is useful because widening of the popliteal hiatus can be checked when posterolateral instability is caused by injury to posterolateral corner [27–29].

Recently, meniscofibular ligament (MFL) of the posterolateral corner extending between the inferolateral portion of the lateral meniscus, just anterior to the popliteus tendon, and the tip of fibular head has been discovered by anatomic studies (Fig. 15) [30, 31]. The MFL may provide stability to the posterolateral corner and future studies are needed to better characterize the anatomy and function of the MFL.

The anatomy and function of the anterolateral complex (ALC) are renewed since 2013 publication by Claes and colleagues rediscovering the anatomy of the anterolateral ligament (ALL) [32]. Historically, Paul Segond described a remarkably constant avulsion of “pearly, resistant, and fibrous band” at the anterolateral aspect of the knee, the commonly named Segond fracture in 1879. However, to date, as at the time of MPFL’s discovery, there are much controversy about ALL’s anatomy whether it is a “clear ligament structure,” “thickening of capsule,” “fibrous band,” or “complex structure.” Recently, agreement has been reached that the ALL does indeed exist as a structure within the ALC composed of ITB with the Kaplan fiber system, the lateral meniscus, ALL, and anterolateral capsule [25]. The origin of ALL is proximal and posterior to the femoral lateral epicondyle and courses superficial to the LCL, and attaches at the tibia midway between the fibular

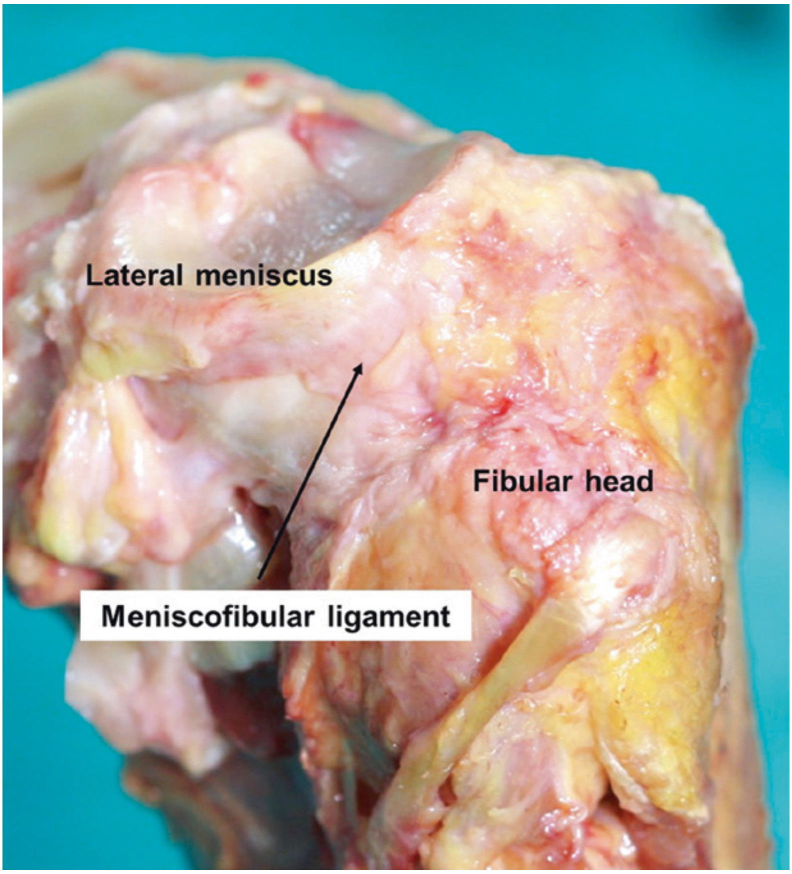

Fig. 15 The meniscofibular ligament (MFL) originates from the inferolateral portion of lateral meniscus and is inserted to the fibular head. It looks like a capsular thickening of posterolateral corner

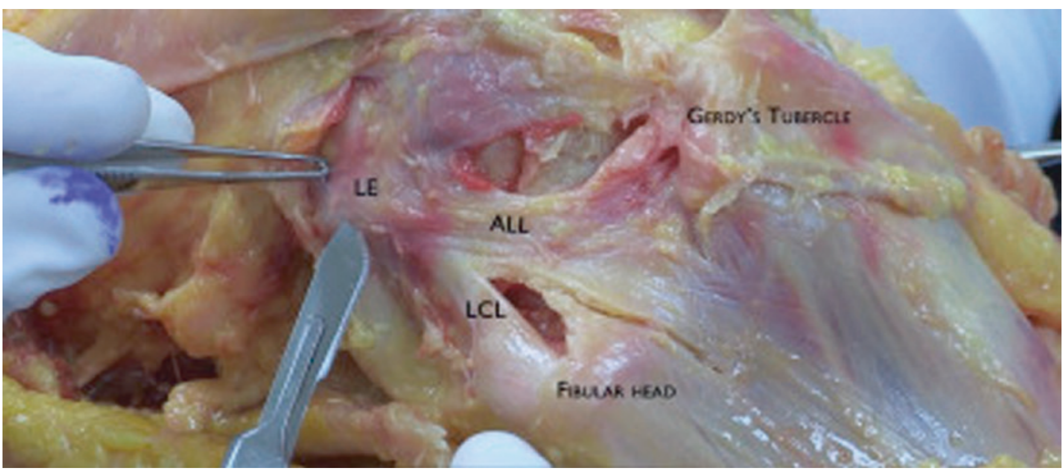

Fig. 16 The anterolateral ligament (ALL) is clearly identified as a distinct structure with an insertion in a fan-like fashion onto the anterolateral tibia. It originates near the lateral epicondyle (LE) and overlaps the lateral collateral ligament (LCL) (From Matthew Daggett, Kyle Busch, and Bertrand Sonnery-Cottet. Surgical Dissection of the Anterolateral Ligament. Arthrosc Tech. 2016 Feb 22;5(1):e185–8. Reprinted with permission.)

head and Gerdy's tubercle [25, 32]. The ALL has an attachment to the lateral meniscus [33]. Daggett and colleagues emphasized that the ALL can be clearly identified as a distinct structure with an insertion in a fan-like fashion onto the anterolateral tibia after careful dissection and precise elevation of the ITB (Fig. 16 Permission) [34]. Helito and colleagues revealed that the ALL was found in all dissected fetal cadaveric specimens and the histological sections of it showed "well-organized," "dense" collagenous fibers with fibroblasts [35]. The ALL has an anisometric behavior and acts as a secondary tibial internal rotation stabilizer to the ACL [25].

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Subjective and Objective Assessments of Knee Function

Dhong Won Lee, Jin Goo Kim and Jin Woo Lim

Abstract

There are numerous evaluation tools used to assess subjective and objective status after knee injury or surgery. To evaluate appropriate results of treatment, methods of evaluation should include patient-oriented measures such as patient satisfaction and health-related quality of life (HRQOL), as well as outcomes of objective measures. Regarding subjective assessments, scoring systems developed and verified by experts group are widely used such as Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) score, Knee Injury and Osteoarthritis Outcome Score (KOOS), and International Knee Document Committee (IKDC) subjective score. Since psychological factors in knee injuries are also an important factor, scales related to this have also been developed. Pre-existing objective assessments to evaluate knee function have limitations in determining real function, so efforts have been made to find more suitable methods of assessing the functional performance. It is becoming common to use the test battery to comprehensively determine the performance of sports activities as much as possible, and to measure them more concisely using the electronical equipment.

Improvements in test battery through advanced digital sensor and Internet technology may lead to easier and real-time measurements of knee performance.

Keywords

Anterior cruciate ligament reconstruction · Subjective score · IKDC · Pivot shift test · Functional performance test · Functional test · Return to sports

D. W. Lee (✉) · J. W. Lim
Department of Orthopaedic Surgery, Konkuk University Medical Center, Konkuk University School of Medicine, Seoul, Republic of Korea
e-mail: osdoctorknee@kuh.ac.kr

J. W. Lim
e-mail: jwlim65300@gmail.com

J. G. Kim
Department of Orthopaedic Surgery, Hanyang University Myongji Hospital, Gyeonggi-do, Republic of Korea
e-mail: boram107@daum.net

Introduction

There are numerous evaluation tools used to document injury severity, effectiveness or treatment, and return to daily life after knee injury. Most of them are based on objective or clinical

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parameters such as radiographic analysis, physical examinations including joint instability, range of motion, muscle strength, and function test. However, to evaluate appropriate results of treatment, methods of evaluation should include patient-oriented measures such as patient satisfaction and health-related quality of life (HRQOL), as well as outcomes of objective measures. Especially, since it is important to objectively evaluate effectiveness of rehabilitation and surgery in treatment of patients, the design of an indicator for results is crucial. A reliable and validated indicator not only takes a role to evaluate progress and results of treatment but also has an effect on evaluation of prognosis, satisfaction levels of patients, medical teams, and protectors, consequential improvement of medical service and direct or indirect cost reduction.

Numerous knee scoring systems, KT-1000 arthrometer test, Lachman test, anterior drawer test, and pivot-shift test have been widely used to determine when to resume physical, sports activities in clinical settings. However, several studies have suggested that these tests are not appropriate predictors of the functional stability of the knee in actual sports activities [1–4]. To overcome the limitations of the aforementioned tests, various functional performance tests (FPTs) have been introduced [5–11].

In this chapter, we will review widely used knee scoring systems, functional performance tests, and investigate noteworthy points for applying appropriate test to patients for reliable and valid results.

Subjective Assessments

The scoring system to evaluate a knee function was firstly introduced by O'Donoghue in 1955 and numerous scoring systems have been described by several authors (Slocum, Larson, Hughston, Barrett, Lysholm, Gillquist, Tegner, Noyes, Muller etc.). However, these knee scoring systems show limitations when confined to specific diseases or anatomical parts, and they have not evaluated the legitimacy and reliability of each evaluation criteria, and put different emphasis on similar criteria. In addition, inconsistent definition of each terminology resulted in different emphasis points, thereby unable to comprehensively include health-related quality of life (HRQL) beyond certain anatomical parts and disease [9, 11–13]. The main concept of HRQL is that various health conditions, physical structure and function, and other social conditions reflect the activity and social participation of patients, which can be evaluated as physical, emotional, and social functions of patients. These HRQL assessment indicators can be classified into overall assessment indicators, such as the 36-Item Short Form Survey (SF-36), and special assessment indicators focused on specific anatomical sites and diseases [14–16]. The SF-36 is a commonly used general health questionnaire that includes 36 items about general status of health. It consists of eight subscales regarding physical function, role-physical, bodily pain, general health, vitality, social functioning, role-emotional, and mental health. These subscale scoring can be converted to 100-point scale, with a score of 0 (worst) to 100 (best). This scale is proven to be validated and widely used with disease-specific scoring systems.

There are several commonly used disease-specific scoring systems for the knee function. The Lysholm, Cincinnati, and Mohtadi scores are developed to evaluate patients with knee ligament injuries, and Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) score is designed to assess knee osteoarthritis (OA). The Knee Injury and Osteoarthritis Outcome Score (KOOS) and International Knee Document Committee (IKDC) subjective score belong to anatomical region-specific scoring systems [17–26].

Early knee function assessments have been used to give subjective marks to questions that experienced clinicians thoughts were of subjective importance (such as Lyssholm, Cincinnati, and Mohtadi scores), which cannot reflect the main functions of patients' daily lives, and thus lead to efforts to create more objective and scientific questions as they enter the twenty-first century. A group of experts should go through procedures to reflect the relative importance of each question in the assessment tools, evaluate completeness, etc., and statistically verify reliability, validity, and responsiveness. Assessment tools that have undergone these verification procedures include WOMAC score, KOOS, and IKDC subjective score [19, 20, 24, 27].

The WOMAC score has been designed to evaluate patients with knee osteoarthritis. This scoring system consists of 24 items categorized to three items: pain (5 items), stiffness (2 items), and function (17 items). The WOMAC score has been widely used and found to be reliable and valid [20, 26].

There is a limitation that WOMAC score, which is a well-designed and verified evaluation tool for knee OA, cannot reflect the satisfaction and living conditions of Asian patients who are familiar with floor life. The evaluation index can be modified by reflecting the culture of each country, and the representative is the Korean Knee Score (KKS), which includes questions that reflect the evaluation of floor life [28]. This evaluation system consists of a total of 41 questions: (1) pain and symptoms 11 questions, (2) 5 questions of mathematical symptoms, (3) 19 questions of physical function, and (4) 6 questions of social and emotional function. As these questions include all 24 WOMAC questions, it has been established that WOMAC score is automatically calculated by measuring KKS only.

The Knee Injury and Osteoarthritis Outcome Scale (KOOS) was developed in 1998 to assess patient subjective reported opinion about their knee injuries. Although this scale was designed to assess patients with knee OA, it can be widely used in patients with knee injuries which can lead to post-traumatic OA. Several studies have revealed validity and reliability of this scale in various knee injuries. This scale has strength in correlation with WOMAC score, which is also designed to assess OA patients [26]. The KOOS consists of 42 items with 5 subscales regarding pain (9 items), symptoms (7 items), function in daily living (17 items), knee-related quality of life (4 items), and function in sports (5 items) [24, 29].

The Lysholm score is subjective outcome measurement tool for knee ligament injuries. This scale is composed of eight items (limp, support, stair climbing, squatting, instability, locking, catching, pain, and swelling) that are converted to 100-point scale, with 100 representing the highest result. This scale already has been shown to be validated and widely used in clinical settings and clinical researches for assessment of knee function [18, 21, 22]. The IKDC score has been developed by the committee from American Orthopaedic Society for Sports Medicine (AOSSM) and the European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA) to provide a standardized assessment tool for knee injuries. The original form of IKDC score has been published in 1993 and revised form has been published in 2000. The IKDC score assesses patient subjective reported score regarding daily and sports activities. The IKDC score consists of 18 questionnaires including symptoms, general function, and sports activities related to a variety of knee disorders that are scores as well as 100-point scale, where a score of 100 represents the best knee function [30]. The IKDC score not only contains more specific question items and practical questions about daily and sports activities compared to the Lysholm score, but also features interval in the form of questionnaires [19, 27, 31, 32].

Tegner activity score is a patient subjective reported score representing levels of activity which developed in 1985 [8]. This scale offers questionnaire form in which patients are asked to choose score ranging from 0 to 10 (10 indicates the highest level) that represents their level of activities. The ratings of Tegner activity score are divided into four distinct groups, with a rating of 0 representing disability due to knee injuries, 1 to 5 corresponding to levels of recreational sport and work-related activity, and 6 to 9 corresponding to high level of sports activity. This scale has been shown to be reliable and valid evaluation tools for patients with meniscal injury, ACL injury, and patellar instability [21, 22, 33].

Psychological factors in patients are also an important factor in deciding to return to sports activities, and it is known that more than 50% of patients who fail to return to sports have a fear of re-injury [34, 35]. The Tampa scale of Kinesiophobia (TSK) score, designed to measure the fear of re-damage after returning to sports activity, is being used to evaluate psychological factor. The TSK scale system has a 17-item self-report checklist using a 4-point Likert scale. Kvist and colleagues [36] reported that 57% failed to recover to pre-damage levels in the 3–4 years after anterior cruciate ligament reconstruction, and their fear of re-damage was reflected in high scores of TSK scale, which had a strong correlation with the low function of the knee joint. Recently, the Anterior Cruciate Ligament-Return to Sport After Injury (ACL-RSI) scale, which can evaluate the psychological readiness to return to sports activities after ACL injury or reconstruction, has been widely used [37–41]. Webster and colleagues [41] have developed the ACL-RSI scale and it is a unidimensional 12-item scale that evaluates three types of responses associated with the resumption of sport following athletic injury: emotions (five items), confidence in performance (five items), and risk appraisal (two items) (Table 1). For 12 items, a 10 cm Visual Analogue Scale is used.

Table 1 Original items in the ACL-Return to Sport after Injury Scale (ACL-RSI) (From Kate E. Webster, Julian A. Feller, Christina Lambros Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery Physical Therapy in Sport 9 (2008) 9–15 Reprinted with permission.)

Scale item	Order in scale	Mean (SD)
Emotions		
1. Are you nervous about playing your sport?	3	57.56 (30)
2. Do you find it frustrating to have to consider your knee with respect to your sport?[a]	6	50.93 (34)
3. Do you feel relaxed about playing your sport?	12	69.64 (26)
4. Are you fearful of re-injuring your knee by playing your sport?	7	52.63 (29)
5. Are you afraid of accidentally injuring your knee by playing your sport	9	55.10 (28)
Confidence in performance		
6. Are you confident that your knee will not give way by playing your sport?	4	65.97 (27)
7. Are you confident that you could play your sport without concern for your knee?	5	62.14 (29)
8. Are your confident about your knee holding up under pressure?	8	67.40 (26)
9. Are your confident that you can perform at your previous level of sport participation?	1	73.10 (25)
10. Are you confident about your ability to perform well at your sport?	11	72.93 (25)
Risk appraisal		
11. Do you think you are likely to re-injure your knee by participating in your sport?	2	59.94 (25)
12. Do thoughts of having to go through surgery and rehabilitation again prevent you from playing your sport?	10	70.35 (30)

Objective Assessments

Measuring the knee laxity is the main method for the anteroposterior instability. There are Lachman test, anterior drawer test, and pivot-shift test as a way to check the degree of anteroposterior laxity and rotational laxity of the knee after ACL reconstruction [42–44]. Machmalbaf and colleagues [44] revealed that the sensitivities of the Lachman test and the anterior drawer test were 93.5% and 94.4%, respectively, indicating that accuracy could be increased when performed under anesthesia. There are several arthrometers that can measure anterior laxity more objectively: KT-1000 Knee Ligament Arthrometer (MEDmetric, San Diego, CA, USA); Genucom Knee Analysis System (FARO Technologies Inc., Lake Mary, FL, USA); and Rollimeter (Aircast Europe, Neubeuern, Germany). Among them, the KT-1000 arthrometer has been reported to be the most accurate and reproducible device [45, 46]. Pugh and colleagues [47] showed that KT-1000 arthrometer and the Rollimeters have superior validity than stress radiographs using Telos device (Telos GmbH, Laubscher, Hölstein, Switzerland). Because anteroposterior laxity measurements are made only in one direction of the sagittal plane and are unable to assess rotational laxity, which is considered a more important evaluation indicator, there is a limit to reflecting the knee function and symptoms.

Recovery of rotational instability is one of the major factors in determining the return to sports after ACL reconstruction, and pivot-shift test is commonly used as a way to assess rotational laxity. However, since the pivot shift is caused by a combination of translation and rotation at the tibiofemoral joint, it is not easy to distinguish the grade of dynamic rotatory knee laxity by manual [48–51]. To overcome this, various studies have been conducted to quantify and accurately measure the results of axis movement inspection, and various measuring instruments using navigation system (Fig. 1) [52–55], electromagnetic sensor (Fig. 2) [56, 57], inertial sensor (Fig. 3) [58–60], and image analysis system (Fig. 4) [61–63] have been developed. However, there are no measurement devices that have been proven to be accurate and reasonable enough to be used in clinical practice, and it will be necessary to develop measuring instruments that are non-invasive and easy to use with high accuracy and validity.

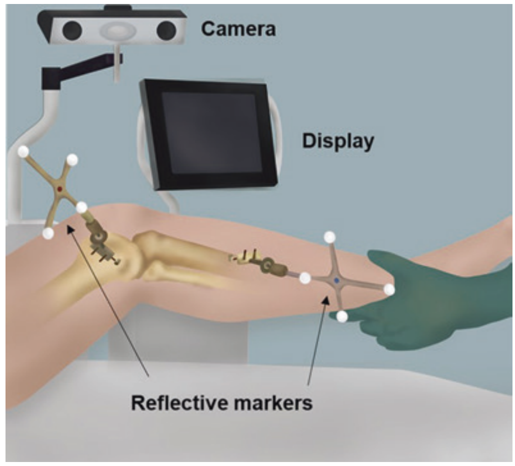

Fig. 1 Navigation system

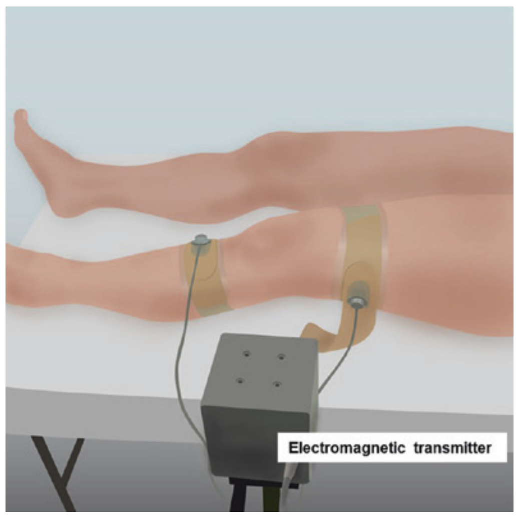

Fig. 2 Electromagnetic sensor

Muscle strength plays an important role in performing the knee function. Therefore, whether or not to restore muscle strength can be a major factor in deciding whether to return to sports. Previous studies have used the isokinetic

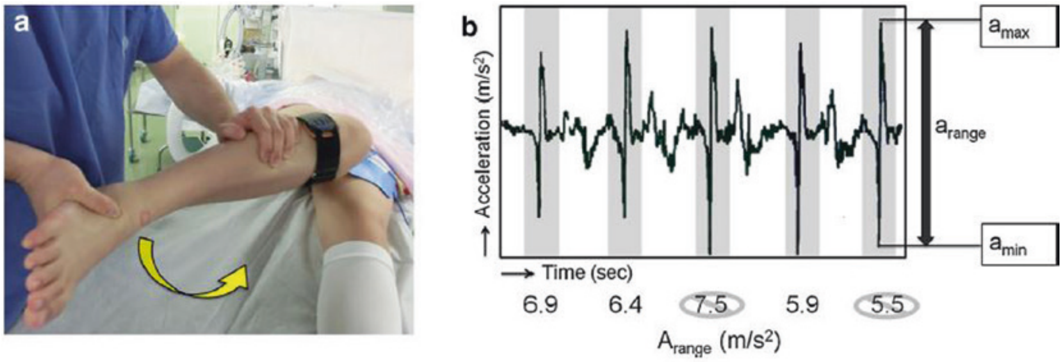

Fig. 3 Inertial sensor (From Kaori Nakamura Hideyuki Koga Ichiro Sekiya Toshifumi Watanabe Tomoyuki Mochizuki · Masafumi Horie · Tomomasa Nakamura · Koji Otabe · Takeshi Muneta Evaluation of pivot-shift phenomenon while awake and under anesthesia by different maneuvers using triaxial accelerometer Knee Surg Sports Traumatol Arthrosc (2017) 25:2377–2383. Reprinted with permission.)

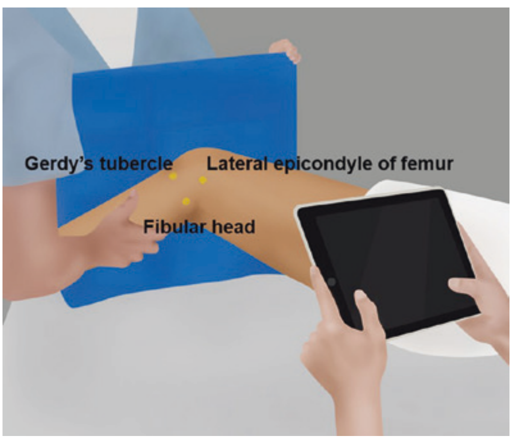

Fig. 4 Image analysis system

strength test as a factor in determining a return to sports activity [34, 64–72]. Isokinetic strength tests have been proven to be a reliable measurement tool for peak torque of knee extensor and flexor. The isokinetic strength test is performed to measure the muscle strength of the involved and uninvolved sides. The subject is seated with the hip flexed at 90 degrees and the position should be maintained by securing straps at the chest, hip, and thigh. The lateral femoral condyle of the knee to be examined is aligned with the rotational axis of the dynamometer and the dynamometer arm is secured to the lower leg 2 cm proximal to the ankle. Measurements are performed at angular velocities of 60°/sec and 180°/sec with four trials for each examination. Extension peak torque per body weight (N·m/kg) and flexion peak torque per body weight (N·m/kg), at angular velocities of 60°/sec and 180°/sec, are also evaluated. At each examination, the highest values are recorded automatically, and the data is categorized according to the muscle strength variables. Results on the usefulness of isokinetic strength test as a means of assessing function recovery of knee after ACL reconstruction are detailed in Chap. 12. However, the limitation of the muscle strength test is that it is performed on open kinetic chain status. Some studies have reported that the isokinetic strength tests have significant associations with running, cutting, and one-legged hop for distance tests, [73, 74] while others have reported that only one-legged hops showed significant correlation [75].

During sporting activity, the lower extremities are continuously subjected to deceleration and acceleration forces, and neuromuscular control system plays a role in regulating these kinematics, so simple quantitative assessments without consideration for neuromuscular control cannot evaluate appropriate knee functions. The efforts have been made to find more suitable functional assessments after knee injury or surgery. Conventionally, single-leg hop tests have been used to decide return to sports after knee ligament injuries, since assessing

Fig. 5 (Fig. 2 of Chap. 12) Single-leg hop for distance test. The subject is asked to hop forward as far as possible, jumping and landing with the same foot. The longest distances for the affected and unaffected limbs are measured in centimeters using a ruler

Fig. 6 (Fig. 3 of Chap. 12) Single-leg hop for jump test. The subject is asked to perform a single deep squat with pause, followed by vertical jumping for maximum height with one leg on a contact mat of a jump analyzer which measures jump height (cm)

single-leg performance is useful because unilateral deficits masked by bilateral leg movements in sports can be detected. The limb symmetry index (LSI) is widely used to calculate the difference in data between the affected limb and unaffected limb, and the threshold LSI for return to sports has been shown to be 80% to 90% [72, 76–78]. There are various types of hop tests, and we usually use the single-leg hop for distance test (Fig. 5: Fig. 2 of Chap. 12) [71, 72, 79–81] and single-leg vertical jump test (Fig. 6: Fig. 3 of Chap. 12) [82]. Using the single-leg hop for distance test in combination with two or more hop tests can increase its sensitivity [73, 78, 80]. Results on the usefulness of single-leg hop tests as a means of assessing function recovery of knee after ACL reconstruction are detailed in Chap. 12.

Tegner and Lysholm [83] used four types of performance tests to evaluate the effectiveness of the brace after ACL injuries. Performance tests performed in this study were course test given in Fig. 8, single-leg hop for distance test, spiral staircase run test, and indoor slope run test

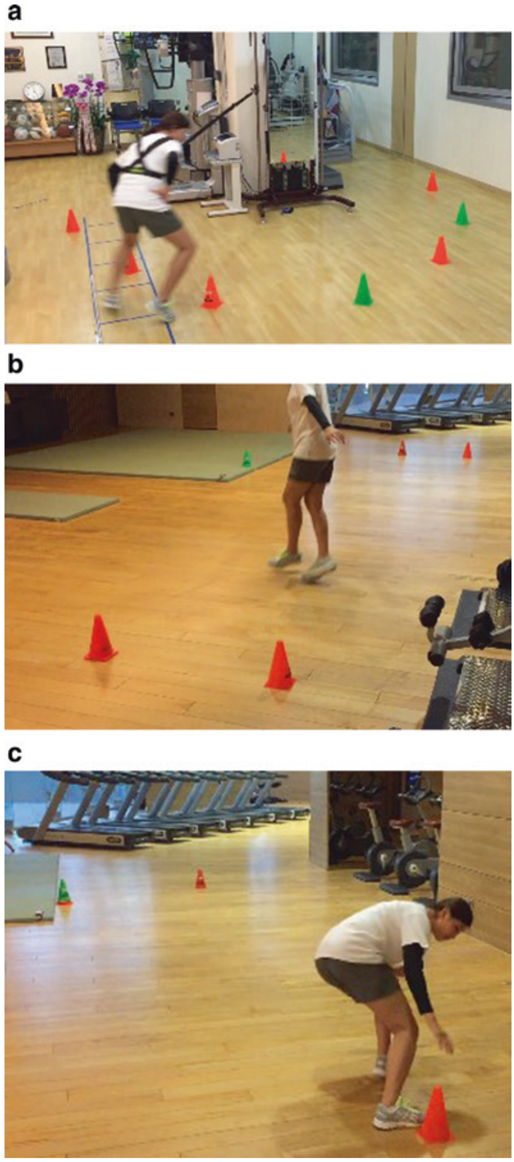

Fig. 7 (Fig. 4. of Chap. 12) **a** Co-contraction test. It reproduces the rotational forces of the knee joint. **b** Carioca test. It reproduces the pivot-shift phenomenon on the tibia. **c** Shuttle run test. It reproduces the acceleration and deceleration forces on the knee joint

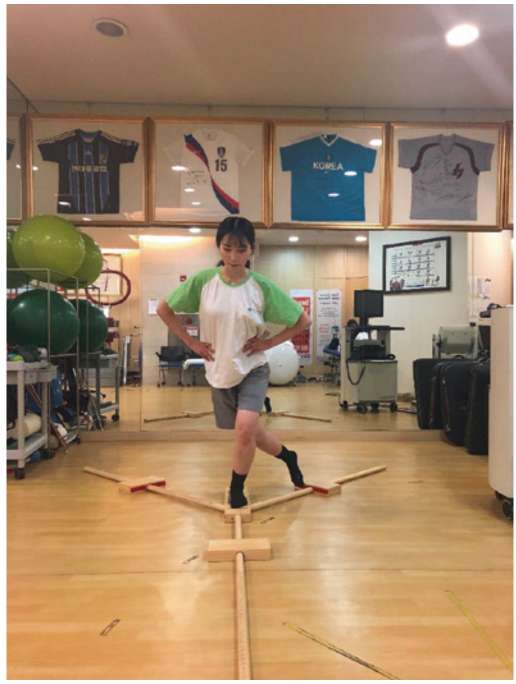

Fig. 8 (Fig. 5 of Chap. 12) Y-balance test. It evaluates dynamic limits of stability and asymmetrical balance in three directions (anterior, posteromedial, and posterolateral)

[83]. More complex three functional tests proposed by Lephart et al. [1] are (1) co-contraction test which reproduces the rotational forces that generate tibial translation; (2) cariocoa test which reproduces the pivot-shift phenomenon; and (3) shuttle run test which reproduces the acceleration and deceleration forces (Fig. 7: Fig. 4 of Chap. 12). It is becoming common to use the test battery to comprehensively determine the performance of sports activities as much as possible, and to measure them more concisely using the electronical equipment. Herbst and colleagues [84] and Hildebrandt and colleagues [85] reported seven functional tests (the two-leg stability test, one-leg stability test, two-leg countermovement jump, one-leg countermovement jump, plyometric jumps, speedy test, and quick feet test) with high level of test–retest reliabilities.

Recently, a movement analysis such as Landing Error Scoring System (LESS) is included in a test battery [86]. Many authors reported that LESS may be a significant predictor for patients passing all return to sports criteria after ACL reconstruction, because asymmetrical movement patterns such as increased knee valgus are suggested to increase re-injury [87–89]. Another test for assess balance and dynamic control is the Y-Balance Test (YBT), which was derived from the star excursion balance test and is a relatively simple and reproducible test [71, 90] (Fig. 8: Fig. 5 of Chap. 12).

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Evolution of ACL Reconstruction

Shinsuke Kihara, Sean J. Meredith, Benjamin B. Rothrauff and Freddie H. Fu

Abstract

The tissue that would come to be known as the anterior cruciate ligament (ACL) was first described by the ancient Egyptians, but detailed examination of its structure and function did not began in earnest until the nineteenth century. Recognizing the important role of the ACL in stabilizing the knee, early attempts at suture repair through open surgical procedures were associated with high morbidity and poor outcomes. Open ACL reconstruction afforded more consistent stabilization, but it was the introduction of arthroscopy that allowed ACL reconstruction to become one of the most common orthopaedic surgical procedures. In seeking graft isometry, single-incision approaches with transtibial drilling of the femoral tunnel became standard of care, but subsequent biomechanical studies demonstrated that this technique failed to restore joint kinematics due to non-anatomic graft positioning. As a result, anatomic ACL reconstruction has rapidly grown in popularity, yet its ability to fully restore joint kinematics and prevent post-traumatic osteoarthritis (OA) requires further investigation. Elucidation of the multiple variables that contribute to knee stability will be necessary to further improve the treatment of ACL injury. Emerging surgical techniques, devices, and tissue-engineering strategies may also expand treatment strategies, including the possibility of augmented ACL repair for the appropriate indications.

Keywords

Anterior cruciate ligament · Reconstruction · Repair · Arthroscopy · Autograft · Allograft

First Description of ACL Structure and Function

The first description of the structure later known as the anterior cruciate ligament (ACL) dates back to ancient Egypt (3000 BC), with Hippocrates (460–370 BC) subsequently reporting a ligament pathology that produced anterior tibial subluxation [1, 2]. However, the Greek physician Claudius Galen (131–201 BC) gave the ACL its modern name, derived from the Greek "ligamenta genu cruciate." Despite its known existence for millennia, the function

S. Kihara · S. J. Meredith · B. B. Rothrauff · F. H. Fu (✉)
Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, PA, USA
e-mail: ffu@upmc.edu

B. B. Rothrauff
e-mail: rothrauff.benjamin@medstudent.pitt.edu

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of the ACL was not formally investigated until more recent history. Brothers Wilhelm Weber (1804–1891) and Eduard Weber (1806–1871) demonstrated that transection of the ACL produced abnormal anterior–posterior movement of the tibia relative to the femur. They also reported that the ACL consisted of two bundles, which were tensioned at different degrees of knee flexion and differentially contributed to the roll and glide mechanism of knee.

Early Treatment of ACL Injury

The first case of ACL repair was performed in 1895 by Sir Arthur Mayo-Robson (1853–1933) and involved a 41-year-old miner [3]. Through an open procedure, the proximally torn ACL was sutured to the femoral insertion with catgut ligatures. At 6-year follow-up, the patient considered his leg "perfectly strong" but range of motion was objectively reduced. Following this first surgical report, suture repair grew to become the mainstay of the treatment for ACL tears until the early 1980s, a transition prompted by a seminal report in 1976 in which John Feagin and Walton Curl presented 5-year results of 32 Army cadets who had undergone direct ACL repair [4]. Almost all patients suffered some degree of instability, two-thirds experienced persistent pain, and 17 of 32 sustained a re-injury during the follow-up period. The authors concluded, "It was our hope that anatomic repositioning of the residual ligament would result in healing. Unfortunately, long-term follow-up evaluations do not justify this hope." Poor clinical outcomes with non-augmented ACL repair, coupled with improving techniques for ACL reconstruction (ACLR), hastened the move away from repair and toward reconstruction [5].

Emergence of ACL Reconstruction

Twenty-two years following the first report of ACL repair, Ernest William Hey Groves performed the first ACL reconstruction in 1917 [6]. He detached a strip of fascia lata from its tibial insertion and passed it from proximal to distal through femoral and tibial bone tunnels (Fig. 1). A year later (1918), Smith reported on nine cases he had treated with Hey Groves' technique. In 1919, Hey Groves presented an additional 14 cases in which he modified his method. Despite the promising results described by these early pioneers, debate in the following 50 years was less over primary ligament repair versus reconstruction, but whether any procedure should be performed at all. Nevertheless, novel (mostly open) reconstructive approaches were investigated in the ensuing half-century, including descriptions of various surgical techniques, graft sources, and fixation methods.

Graft Sources

Fascia lata. The fascia lata enjoyed early popularity as a graft for ACLR due to the seminal report by Hey Groves [6]. 100 years later (2017), the fascia lata still represents a viable autograft choice as its sizing is moderately

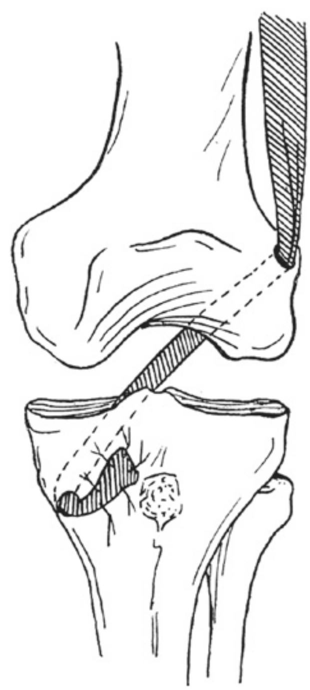

Fig. 1 Original Hey Groves ACL reconstruction technique in which a portion of the fascia lata was passed proximal to distal through bone tunnels. (Adapted with permission from *The Lancet*, Elsevier)(6)

tunable and its harvest has not been associated with the deficits in muscle strength induced by alternative grafts such as the hamstrings and quadriceps tendons [7].

Meniscus. Zur Verth replaced the ACL with the torn lateral meniscus, which he left attached distally and sutured against the ligament remnants proximally [1, 2]. The meniscus was seen as a suitable ACL replacement graft until the late 1970s when the contribution of the meniscus to knee stability and force transmission across the joint was increasingly appreciated. As a result, the meniscus was finally abandoned as a graft by the end of 1980s.

Bone–patellar tendon–bone (BPTB). The BPTB became one of the most common graft sources for ACLR, especially in patients seeking a fast return to sports. In 1976, Kurt Franke of Berlin reported good long-term functional outcomes following 130 ACL reconstructions using a free graft of the central third of the patellar tendon [8]. Given the promising long-term results, coupled with reliable and reproducible surgical technique, the BPTB became and remains one of the most popular graft sources [9, 10]. On the other hand, it became apparent that harvesting autogenous patellar tendon grafts could result in extension strength deficits and was more commonly associated with certain intraoperative and post-operative complications such as patellar fracture [11], patellar tendon rupture [12], flexion contracture, patellar tendonitis, and anterior knee pain [13–15]. In response, some surgeons started experimenting with using a central portion of the quadriceps tendon.

Quadriceps tendon. In 1984, Walter Blauth reported good results for 53 patients who underwent ACLR using quadriceps tendon [16]. The quadriceps tendon, however, never gained the same level of popularity as the BPTB or hamstring grafts despite experimental studies confirming its excellent mechanical properties [17]. Today, the quadriceps tendon is most commonly utilized as a secondary graft source in the revision setting or when other graft sources are compromised [18], but it is increasingly employed in primary ACLR.

Hamstrings tendons. The first use of hamstrings tendons as a graft was reported in 1934 by Italian orthopaedic surgeon Riccardo Galeazzi, who described a technique for ACL reconstruction using the semitendinosus tendon [1, 2, 19]. McMaster et al. in 1974 used the gracilis tendon alone [20]. In 1982, Brant Lipscomb started using both the semitendinosus and gracilis tendons as a double-strand graft left attached to the pes anserinus [21]. Six years later, following from Lipscomb's experience, Marc Friedman pioneered the use of an arthroscopically assisted four-strand hamstring autograft technique, which, despite several smaller modifications, set the standard for ACL reconstruction with hamstrings for the next 25 years [22]. Long-term follow-up studies have since confirmed almost equivalent results among graft choices regarding knee function and prevalence of osteoarthritis (OA) [23, 24].

Allograft. Allograft reconstruction of the ACL was an attractive proposition as it avoids the need for graft harvest and associated donor site morbidity and prevents weakening of external ligament and tendon structures which contribute to overall joint stability. In 1986, Konsei Shino and associates became one of the first groups to publish clinical results of 31 patients who had received allogenic reconstruction of the ACL utilizing mainly tibialis anterior and Achilles tendon allografts [25, 26]. After a minimum follow-up of 2 years, all but one patient had been able to return to full sporting activities. Subsequent publications by Richard Levitt and colleagues reported excellent results in 85% of cases at 4 years. These early reports of success paved the way for allografts to achieve relative popularity [27]. Unfortunately, the increased risk of viral disease transmission (e.g., HIV, Hepatitis C) associated with allografts in the 1990s created a significant setback for this technology. Allograft reconstruction has only recently regained some ground through the introduction of improved "graft-friendly" sterilization techniques [28]. Today, allograft tissue remains an attractive and reliable alternative to autograft in the primary and revision setting despite the rather considerable cost [29]. Furthermore, ACL reconstruction with allograft has an increased failure rate in young patients and should be avoided in this particular patient population if possible [30].

Synthetic. The use of synthetic materials has intrigued surgeons for over 100 years. It was hoped that use of synthetic grafts stronger than soft tissue equivalents could be developed, simplifying the operation by avoiding graft harvest and associated donor site morbidity. In terms of in vitro behavior, most synthetic grafts showed fatigue resistance on cyclic loading beyond the limit of human ligament endurance [31]. However, early biomechanical tests did not fully consider the biological environment in which the grafts would function. Stryker made a polyethylene terephthalate (i.e., Dacron) ligament replacement device commercially available in the 1980s. Poor outcomes were reported in 1997 by Wolfgang Maletius and Jan Gillquist at 9-year follow-up of 55 patients [32]. By that time, 44% of grafts had failed, 83% had developed radiographic signs of osteoarthritis, and only 14% presented with acceptable stability. The production of the Dacron ligament device was finally discontinued in 1994.

In the late 1970s, Jack Kennedy introduced a ligament augmentation device (LAD) made of polypropylene, which became known as the “Kennedy-LAD” [31]. Lars Engebretsen and associates commenced a randomized controlled study that enrolled 150 patients in 1990 to assess the merits of the LAD compared to acute repair and reconstruction with autologous BPTB [5]. Both acute repair and repair with the LAD failed in up to 30% of cases, and the authors hence discouraged any form of repair other than autograft reconstruction [33]. Various synthetic ACL grafts composed of other materials, including GoreTex, PDS, Eulit, and Polyflex, were introduced during the same period [34]. The hope of finding a reliable and durable off-the-shelf ACL replacement was soon dampened by a flood of reports on an increasing amount of fatigue failures, including graft re-rupture, chronic synovitis, tunnel widening through osteolysis, foreign body reaction, and poor incorporation of the synthetic grafts into the host bone [35, 36]. Nevertheless, the Kennedy-LAD, together with the Leeds-Keio and the LARS ligament, remain available as augmentation devices to this day.

Fixation Methods

For much of the twentieth century, fixation of the graft during ACL reconstruction entailed the simple suturing of the protruding parts of the graft to the periosteum at the tunnel exits. Kenneth Lambert was the first to describe the use of an interference screw. In 1983, Lambert used a standard 6.5 mm AO cancellous screws of 30 mm in length, which he passed from outside-in alongside the bone blocks of BPTB grafts [37]. Thereafter, interference screws gained wider attention due to Kurosaka’s work examining the strength of various fixation methods, which he published in 1987 [38]. In this study, it was found that specially designed large diameter cancellous screws provided the strongest fixation. Within a few years, interference screws made of biodegradable materials such as PLA (polylactic acid), PGA (polyglycolic acid), and TCP (tri-calcium phosphate), or any combination thereof, also became available [39, 40] (Fig. 2). In 1994, Ben Graf, Joseph Sklar, Tom Rosenberg, and Michael Ferragamo introduced the Endobutton, a ligament suspensory device that works as a tissue anchor by locking itself against the cortex of the femoral condyle [41] (Fig. 3). Although critics have highlighted theoretical biomechanical disadvantages of suspensory fixation compared to aperture fixation, including the windshield wiper and bungee effects, clinical results between the various fixation methods have been relatively equivalent [42, 43].

Extra-Articular ACL Reconstruction

The complexities of intra-articular reconstructions were often fraught with peril and clinicians were eager to find ways to simplify stabilizing

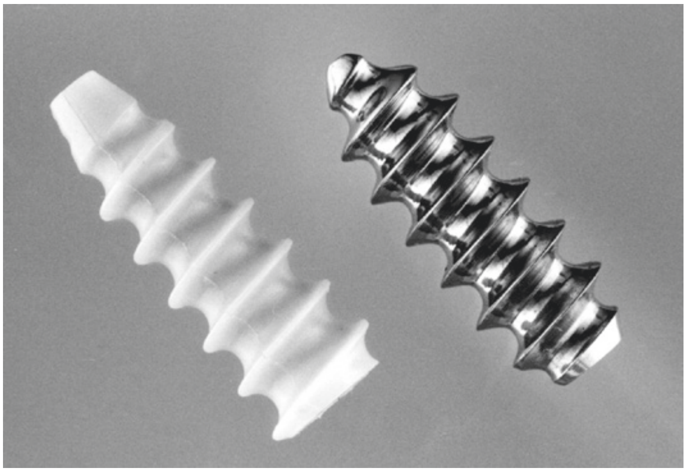

Fig. 2 Bioabsorbable and metal interference screws. (Adapted with permission from *Arthroscopy*, Elsevier) (40)

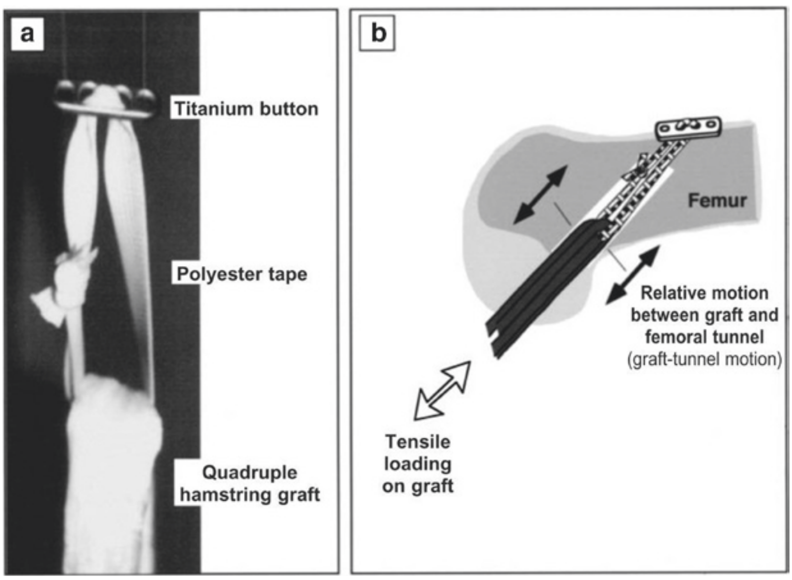

Fig. 3 **a** Femoral fixation construct for a quadruple-stranded hamstring graft with a polyester loop and Titanium Endobutton. **b** Schematic of graft-tunnel motion as it may occur when the graft is loaded either in cyclic tensile testing or in vivo during knee motion. (Adapted with permission from *KSSTA*, Springer Nature) (42)

procedures for ACL deficiencies without opening the joint. Various extra-articular substitution procedures with and without ACLR were developed and have since fallen out of practice. Most of those procedures addressed anterolateral instability, trying to control the pivot-shift phenomenon by using methods of capsular tightening, various tendon and fascial slings to re-route the iliotibial tract, and repositioning of ligament attachments [44]. Extra-articular reconstructions gradually fell out of favor when reports emerged about their unpredictability in satisfactorily decreasing tibial subluxation [45–47]. Most additional extra-articular procedures had vanished by the end of 1990s.

Emergence of Arthroscopy

Among various developments to improve the success of ACL reconstruction, one of the most profound advancements occurred in the 1970s, led by Robert Jackson and David Dandy, who improved arthroscopic instruments. The first arthroscopically assisted ACL reconstruction was performed by David Dandy in 1980 [48]. After several years of debate over the relative superiority of open versus arthroscopic surgery, Bray et al. reported in 1987 that arthroscopic ACL reconstruction was associated with less post-operative morbidity, improved cosmesis, increased speed of recovery, and greater range of motion [49]. It was during this time that the modern techniques of ACL reconstruction most firmly solidified, including the widespread use of arthroscopy fiber optic and television technology, a narrowing of the common graft source to BPTB and hamstrings, and confirmation of graft fixation methods.

Changing Paradigms—From Isometric to Anatomic Reconstruction

With a growing frequency of ACL reconstruction, there was a commensurate interest in understanding how to best perform the procedure. In the 1960s, based on the notion that the ideal anterior cruciate ligament graft should be isometric either in part or in the mechanical summation of its parts, the biomechanical concept of graft isometry arose [50]. The isometric point was defined by Artmann and Wirth in 1974 [2, 51]. In particular, the femoral tunnel was to be placed within the posterosuperior portion of the anatomic footprint, close to the "over-the-top" position. While the intention for isometric position was considered feasible through a single-incision approach with transtibial drilling, it became apparent that any non-anatomical single-bundle technique was unable to fully restore normal knee kinematics or reproduce normal ligament function. By extension, it was hypothesized that the relatively disappointing clinical results and high prevalence of osteoarthritis following ACL reconstruction were due to the inability to restore normal knee kinematics [52, 53].

As a result, the beginning of the twenty-first century saw a movement away from the concept of isometry and toward increased understanding of physiological and anatomical principles, led most prominently by Kazunori Yasuda and Freddie Fu [54]. In 1997, Sakane et al. examined the in situ force distribution between the anteromedial (AM) and posterolateral (PL) bundles, finding that the magnitude of forces in the PL bundle was significantly affected by the flexion angle while forces in the AM bundle remained relatively constant [55]. This study was the first to suggest that reconstruction techniques should focus on the role of both bundles. This prompted Fu to explore possible merits of anatomic ACL reconstruction [56–58] (Fig. 4).

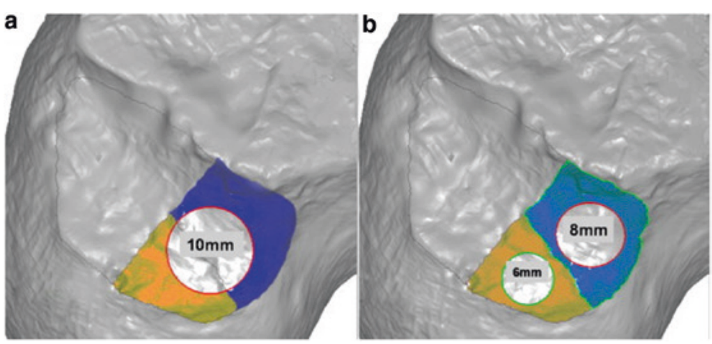

Fig. 4 Schematic of native femoral footprint on CT 3D reconstructed model showing potential position of one or two tunnels coinciding with single-bundle or double-bundle ACLR. (Adapted with permission from *Arthroscopy*, Elsevier) (57)

Contemporary ACL Reconstruction—From Anatomic ACLR to Individualized, Anatomic ACLR

As it became increasingly evident that reconstruction techniques were unable to restore normal knee kinematics and clinical results were still lacking, there was a shift in focus to the anatomy and physiology of ACLR [2]. In 1997, the importance of the two ACL bundles in providing stability to anterior tibial loads was shown in a biomechanical analysis [55]. This was the first study to suggest that taking both bundles into account during reconstruction may be necessary to reproduce the in situ forces of the native ACL. Traditional non-anatomic reconstructions were shown biomechanically to fail to limit anterior tibial translation in response to a combined valgus and internal tibial torsional force [59]. Anatomic double-bundle reconstruction most closely restored the knee kinematics and in situ ACL forces in response to both an anterior tibial load and combined rotatory load [52]. The biomechanical successes led to the interest in anatomic double-bundle ACLR for improving clinical outcomes [56]. Although the clinical outcomes of anatomic single-bundle versus anatomic double-bundle are not conclusive, the literature supports the focus remaining on the *anatomic* reconstruction [54, 57].

Non-anatomic femoral tunnel location has been identified as the most common reason for ACL graft failure in the Multicenter Anterior Cruciate Ligament Revision Study (MARS) database [60]. Additionally, worse clinical outcome measures have been correlated with femoral tunnels farther from the anatomic insertion site [9]. Given the focus on anatomic femoral tunnels, the transtibial ACLR technique has been questioned, and found that it does not consistently position the femoral tunnel in the anatomic ACL insertion site [61]. Thus, independent femoral tunnel reaming through an anteromedial portal has subsequently gained popularity. Anteromedial portal reaming has been shown to more accurately position the femoral tunnel in the center of the ACL footprint, as compared to transtibial drilling where the tunnel is consistently superior and anterior to the center of the footprint [62]. This has been reported in multiple studies and confirmed with a meta-analysis [63].

More recently, the anatomic approach has been refined to the "*individualized, anatomic ACLR concept*" [57, 64]. The primary objective is the functional restoration of the ACL to its native dimension, fiber orientation, and insertion sites. The literature has shown that excellent outcomes can be expected when either a single-bundle or double-bundle technique is individualized to the patient and tunnel placement is anatomic [65]. A crucial aspect is recreating the anatomy in an individualized manner based on the size of the native ACL and the bony morphology of the knee, and in this light, individualized graft sizing has become a more recent focus. The Multicenter Orthopaedic Outcomes Network (MOON) Cohort Study showed that ACL graft sizes 8 mm or less were associated with increased risk for revision surgery [66]. However, the size of the graft must be considered in relation to the individual patient's native anatomy (Fig. 5). Autograft reconstruction options, including quadriceps tendon, bone–patellar tendon–bone, and hamstrings tendon, vary in size for each patient and do not necessarily reliably recreate the native ACL size [67]. Additionally, these autograft options do not correlate well with patient characteristics, such as height and weight. Restoring the native ACL femoral and tibial insertion site size is recommended, but with the knowledge that the ACL midsubstance is about 50% of the cross-sectional area of the tibial insertion [68]. In the senior author's practice, a successful anatomic reconstruction aims to use a graft with an area between 50 and 80% of the native tibial insertion (Fig. 6).

As the individualized, anatomic ACLR concept has evolved so too has the surgical technique. The arthroscopic technique is optimized with a three-portal approach. A standard high anterolateral portal is initially used for access and diagnostic arthroscopy, followed by a transtendinous anteromedial portal for improved

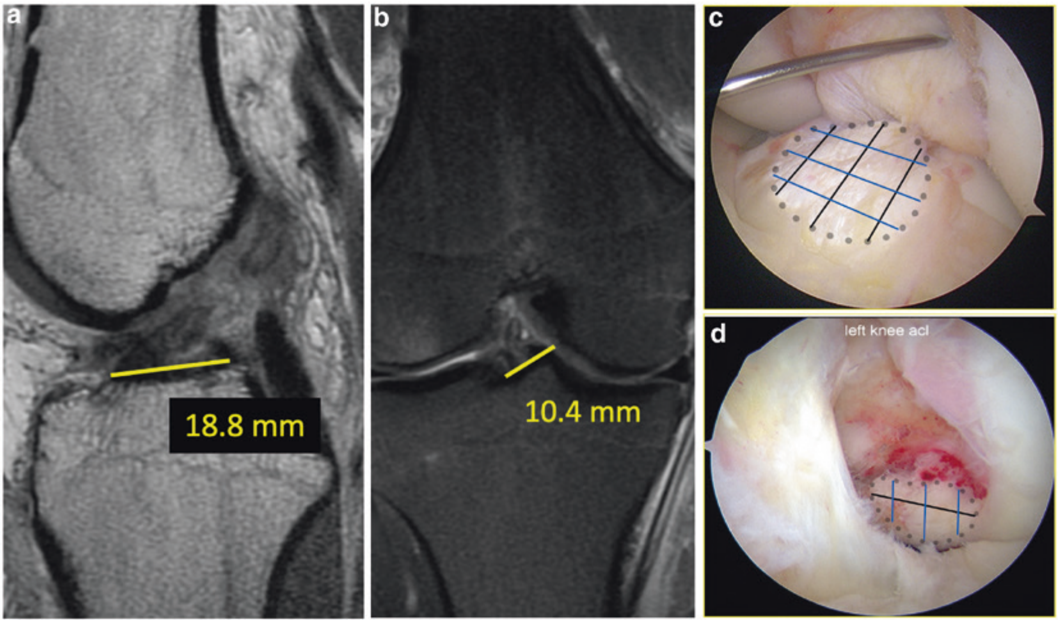

Fig. 5 Determination of native tibial insertion site dimensions of ACL, as performed for individualized anatomic ACLR. Measurement of **a** sagittal and **b** coronal ACL length at tibial insertion site on MRI. Intraoperative measurement of **c** tibial and **d** femoral insertion sites

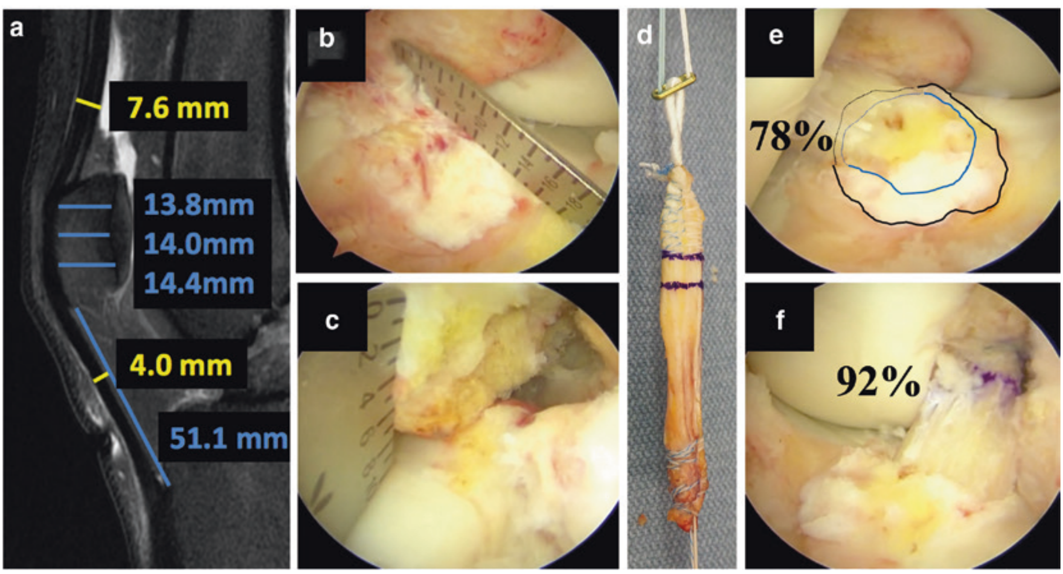

Fig. 6 Example of individualized anatomic ACLR case. **a** Preoperative measurement of potential autograft dimensions on MRI and ultrasound (not shown). Confirmation of **b** tibial and **c** femoral insertion sites with arthroscopic ruler. **d** Given this patient's sizing of possible grafts, native ACL dimensions, and sporting activity, a soft-tissue quadriceps tendon autograft was most appropriate. The graft restored **e** 78% of the native tibial insertion site area and **f** 92% of the native femoral insertion site area. Black lines outline native tibial footprint; blue lines outline graft footprint within native footprint

visualization of the femoral footprint, and an accessory anteromedial medial portal for transportal femoral tunnel reaming. The primary current day graft options include autograft quadriceps tendon with or without bone plug, autograft BPTB, and autograft hamstring tendons. Allografts are avoided in young patients when possible given the high rates of failure in the young athletic population [69]. Quadriceps tendon and patellar tendon thicknesses are measured preoperatively on MRI, and hamstring tendons are measured on ultrasound [70, 71]. The graft choice is individualized for each patient based on many factors including the size matching, patient age, and patient activity level. Soft tissue graft fixation is usually performed with suspensory fixation on the femoral side, but interference screws are also an option. To date, no one fixation technique has been shown to be superior [72]. Grafts with bone blocks are commonly fixed with interference screws, but again suspensory fixation is an option. Tibial sided fixation for all grafts most commonly performed with interference screws gives the ease of insertion.

Future of ACL Repair and Reconstruction

Anatomic ACLR and Post-Traumatic OA. The recent transition from transtibial to transportal drilling due to an intended transition from non-anatomic to anatomic ACL reconstruction has yet to permit long-term follow-up on the relative efficacy of anatomic ACLR. On the other hand, biomechanical and short-term clinical studies demonstrated superior objective stability following anatomic (versus non-anatomic) ACLR, while patient-reported outcomes were largely equivalent [73, 74]. Conversely, registry studies found that transportal drilling was associated with higher re-tear rates than transtibial drilling [75], while subsequent studies found no differences in failures rates between drilling techniques [76], suggesting a learning curve with transportal (i.e., anatomic) drilling. The abrupt transition from transtibial to transportal drilling also precludes randomized controlled trials comparing the two techniques.

In cohort studies employing quantitative MRI mapping of cartilage thickness, DeFrate and colleagues found increased cartilage thinning 2 years following non-anatomic ACLR, a phenomenon not seen in anatomically reconstructed knees [77, 78]. In one of the few long-term studies on outcomes following anatomic ACLR, Järvela et al. [79] found increased rates of OA in anatomically reconstructed knees, as compared to contralateral healthy knees, but an-anatomic ACLR group was not included. Consequently, while it appears that anatomic ACLR does not completely obviate the long-term incidence of post-traumatic OA, whether it mitigates the risk as compared to non-anatomic ACLR remains unclear. It is noteworthy that transportal drilling may be considered a prerequisite for anatomic tunnel positioning, yet does not guarantee successful placement. To that end, a recent systematic review evaluating purported “anatomic” ACLR studies found substantial underreporting of surgical details to adequately conclude that anatomic tunnel placement was likely achieved [80]. In light of these findings, the authors reaffirmed the need for improved surgical description in line with the previously validated anatomic ACL reconstruction scoring checklist (AARSC) [30].

Novel Imaging Modalities. Radiographic scales remain the gold standard for the diagnosis of OA, but the slow progression of arthritic changes following ACLR necessitates improved methodology for earlier diagnosis, which would then provide the theoretical prospect of preventative intervention. Novel sequences of MRI have shown promise in detecting early compositional and structural changes in the articular cartilage following trauma and surgery [81, 82]. In fact, a recent study by Chu et al. [83] utilizing ultrashort echo time (UTE)-T2* mapping suggested that perturbed cartilage could recover its native composition 2 years following anatomic ACLR. However, such findings are preliminary and require confirmation and further exploration. Given the post-traumatic upregulation in inflammatory mediators following ACL injury, it may also be possible (and necessary) to supplement ACLR with biological mediators to further reduce the risk of post-traumatic OA. For instance, Lattermann et al. have commenced a multicenter clinical trial and investigated the effect of pre-operative, intra-articular corticosteroid injection on joint health following ACLR [84].

Role of Anterolateral Complex. As anatomic ACLR has progressively supplanted non-anatomic techniques, recent debate regarding the anterolateral structures of the knee and their contributions to stability has arisen following the assertion of a discreet ligament in the anterolateral capsule, the putative anterolateral ligament (ALL) [85]. While numerous biomechanical studies have affirmed that the ACL is the primary restraint to anterior tibial translation and internal rotation [86–89], the anterolateral capsule and the capsulo-osseous layer of the iliotibial band (i.e., ALL) are secondary constraints. At a recent meeting of the anterolateral complex (ALC) Consensus Group, it was concluded that there is presently insufficient clinical evidence to support clear indications for lateral extra-articular procedures as an augmentation to ACL reconstruction [90]. Resolution of the current uncertainty would be facilitated by further elucidation of the contributions of numerous variables to rotatory stability, including meniscal tears, posteromedial meniscocapsular injury (i.e., ramp lesions), bony morphology, general laxity, and gender, among others [91]. Objective, quantitative measures of knee instability are also needed to better map injury to particular knee structures with worsening instability, of which there are several emerging devices [92, 93].

Augmented ACL Repair. The pursuit of improved outcomes and preservation of joint health following ACL injury have also renewed interest in ACL repair. While past studies of non-augmented suture repair reported high failure rates and poor outcomes, emerging advances in surgical techniques and technology may ultimately support ACL repair as a viable treatment strategy, given the appropriate indications [94]. ACL repairs augmented with either static or dynamic mechanical support have yielded equivocal outcomes. For instance, Gagliardi et al. [95] recently reported a failure rate of 48.8% within 3 years of static suture augmentation of ACL repair in pediatric patients (age 7–18), as compared to 4.7% in the age-matched ACL reconstruction cohort. Conversely, Hoogeslag et al. [96] found dynamic augmented ACL suture repair to be non-inferior to ACL reconstruction at 2-year follow-up when performed in adults.

In addition to mechanical support, biological augmentation may also be useful and/or necessary to overcome the poor healing microenvironment of the joint. To that end, Murray et al. recently reported the 2-year outcomes following biological scaffold (i.e., Bridge-Enhanced) ACL repair (BEAR), finding equivalence with the matched ACLR cohort [97]. The authors noted that the results are promising but preliminary, with longer follow-up and increased sample sizes needed. It also remains to be seen if the BEAR procedure can mitigate post-operative arthritic changes, as previously reported at 1 year in a large animal study performed by this same group [98].

Tissue-Engineered ACL Grafts. Lastly, the emerging field of tissue-engineering promises engineered grafts that overcome the past limitations of synthetic grafts, essentially providing an engineered autograft for an individual patient. One approach is to decellularize a xenograft or allograft, in theory eliminating the immunogenicity of foreign cells. Repopulation of the graft with the patient's cells, either exogenously delivered or endogenously recruited, would in effect provide an autograft without donor site morbidity. The optimized decellularization protocol should preserve the structural and biochemical cues of the native tissue, largely preserving native mechanical properties and promoting tissue-specific differentiation in repopulating progenitor cells. This strategy has shown positive results in preclinical studies [99] but translation to human patients is still unproven. An alternative approach is to fabricate a biomimetic scaffold, with or without cells, by engineering technologies. Scaffolds composed of aligned nano- or microfibers mimicking the aligned collagen fibrils of native tendon or ligament can be fabricated by electrospinning [100, 101] or knitting/weaving devices adapted from textile technology [102].

Conclusion

While the ACL has long been recognized as an important structure for knee stability, rigorous investigation of its function and reliable techniques for its restoration are a recent development of the past half-century. The introduction of arthroscopy reduced the morbidity of ACLR but indirectly encouraged enhanced surgical efficiency, in turn leading to single-incision transtibial drilling with resulting non-anatomic graft positioning. The contemporary transition to anatomic ACLR is supported by biomechanical and early clinical studies, but the ability of anatomic ACLR to restore native joint kinematics and prevent long-term OA progression remains under investigation. Lastly, emerging technologies offer tremendous promise in better understanding of the multifactorial nature of knee stability. With such understanding, coupled with improved surgical techniques and tissue-engineering strategies, the orthopaedic surgeon will be better equipped to provide the right treatment for each individual patient.

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ACL—Current Understanding of ACL Insertion

Rainer Siebold

Abstract

The femoral insertion of the anterior cruciate ligament (ACL) is in the shape of a crescent, with the lateral intercondylar ridge as its straight anterior border and the posterior articular margin of the lateral femoral condyle as its convex posterior border. After removal of the surface membrane, the configuration of the intraligamentous part of the ACL was a "ribbon-like" ligament. The "double-bundle effect" was created by the twisted flat structure, when the knee was flexed. The flat ACL midsubstance formed a narrow C-shaped bony tibial attachment along the medial tibial spine to the anterior aspect of the anterior root of the lateral meniscus in the area intercondylaris anterior. There were only anteromedial and posteromedial inserting fibers.

Keywords

Flat ACL · Ribbon · C-shaped insertion · Tibial insertion · Femoral insertion · Midsubstance of ACL

R. Siebold (✉)
HKF – International Center for Hip-Knee-Foot Surgery, ATOS Hospital Heidelberg, Bismarckstrasse 9-15, 69115 Heidelberg, Germany
e-mail: rainer.siebold@atos.de; rainer.siebold@me.com

Institute for Anatomy and Cell Biology, INF, Ruprecht-Karls University Heidelberg, Heidelberg, Germany

Femoral ACL Insertion

The femoral insertion of the anterior cruciate ligament (ACL) is in the shape of a crescent, with the resident's ridge (=lateral intercondylar ridge) as its straight anterior border and the posterior articular margin of the lateral femoral condyle as its convex posterior border [4, 5, 10, 12, 16, 19, 30, 35, 37]. The most anterior ACL fibers are aligned posterior, directly along and on the lateral intercondylar ridge which is in extension to the posterior femoral cortex (Fig. 1). This extension creates an angle to the femoral shaft axis which varies between 0° and 70° [5, 11, 21, 35, 37, 39]. The most posterior fibers of the femoral ACL insertion are blending with the posterior cartilage of the lateral femoral condyle and with the periosteum of the posterior femoral shaft [4, 5, 10, 11, 16, 21, 33, 34, 37, 39, 45]. In 2006, Mochizuki et al. [26] described the femoral insertion to be not "oval" "but rather flat" and "very similar to the midsubstance configuration of the ACL after removal of the ligament surface membrane." The authors differentiated between the main femoral straight attachment of the midsubstance fibers along the intercondylar ridge and the attachment of the thin fibrous tissue which extended from the midsubstance fibers and broadly spread out like a fan on the posterior condyle (="fan-like extension fibers") [25]. These two different structures form a fold at the border between the midsubstance fibers and the

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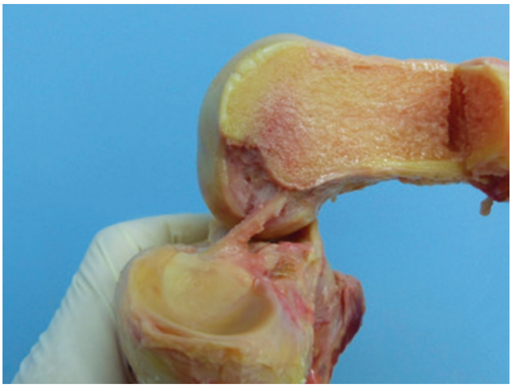

Fig. 1 Macroscopic aspect of right knee with ACL. The extension of the posterior femoral cortex is the direct attachment of the ACL along the intercondylar ridge (resident's ridge)

fan-like extension fibers in knee flexion. Iwahashi et al. [21] described these main (anterior) femoral attachment of the midsubstance fibers in the depression between the lateral intercondylar ridge and 7–10 mm anterior to the articular cartilage margin as "direct" femoral ACL insertion in which dense collagen fibers were connected to the bone by a fibrocartilaginous layer. Sasaki et al. [35] reported a narrow "direct" ACL insertion area posterior and along the lateral intercondylar ridge." The "indirect" ACL insertion was located just posterior to the direct attachment with ACL fibers from Type I collagen blending into the posterior cartilage [37]. Smigielski et al. [45] reconfirmed above descriptions of the femoral anatomical attachment after dissections in 111 cadaver knees with removal of the surface membrane and performed macroscopic measurements and histologic investigations. The authors also described the whole ACL to be "ribbon-like" [45].

Dimensions of the Femoral ACL Insertion

The description of the size of the femoral insertion varies largely. According to the literature, the insertion area is in the range between 46 and 230 mm^2, the long axis has a length between 12 and 20 mm, and the width between 5 and 13 mm [2, 4, 5, 8, 10, 11, 16, 21–23, 30, 35, 37]. Iwahashi et al. [21] measured the direct femoral attachment to be 17.9 mm in length and 8.0 mm in width and Sasaki et al. [35] 17.7 mm and 5.3 mm, respectively. Smigielski et al. [45] reported a mean length of the long axis along the lateral intercondylar ridge of 16.0 mm (range 12.7–18.1 mm) and a mean width of 3.5 mm (range 2–4.8 mm).

Midsubstance of ACL: Ribbon? Bundles?

There is also a big variety of reports on the shape of the ACL midsubstance. It was described as "irregular," "oval," "corded," "bundled," and "flat" [2–5, 10, 16, 22, 23, 30, 39, 45]. In 1975, Girgis et al. [16] found the midsubstance of the ACL to be broad and flat with an average width of 11.1 mm. Welsh [47] and Arnoczky [4] wrote that the ACL is a collection of individual fascicles that fan out over a broad flattened area with no histological evidence for two separate bundles [4, 8, 10, 30, 47]. In contrast, other authors differentiated between anteromedial and posterolateral bundles [1, 5, 11–13, 15, 16, 18, 24, 28, 39, 40] or three separate ACL bundles [2, 29, 32]. According to Arnoczky et al. [4], the bundle anatomy oversimplifies somewhat as the ACL is actually a continuum of fascicles. In 1991, Amis and Dawkins [2] described that it was "sometimes difficult to separate the ACL into three discrete bundles. In this case the anterior aspect of the ACL was folded itself in flexion suggesting an arrangement of bundles. It was still possible to develop a three-bundle structure corresponding to the folding, but it felt, that the tearing apart was artefactual." In older specimens, however, the separate bundles were often obvious. Amis and Dawkins [2] concluded "that the ACL wrinkles into the appearance of three bundles as the knee flexes. These bundles are often separate structures, twisted together during flexion, but the use of the dissector to separate the fibers bundles can cross the threshold between demonstration of bundles and their creation."

In 2006, Mochizuki et al. [25, 26] emphasized "that – after removal of the surface membrane—the configuration of the intraligamentous part of the ACL was not oval" "but rather flat, looking like 'lasagna'," 15.1 mm wide and 4.7 mm thick, and in 2015 Smigielski et al. described the ACL as a "ribbon-like" ligament with an average width of 12.2 mm (range 10.4–14.0 mm) and an average thickness of only 3.5 mm (range 1.8–4.8 mm). The authors observed that the "double-bundle effect" was created by the twisted flat ribbon-like structure of the ACL from femoral to tibial, which leads to the impression of two or three separate bundles when the knee was flexed [42, 45].

There is also a wide range of reports on the cross-sectional area of the midsubstance. Harner et al. [17] calculated approximately 40 mm^2, Hashemi et al. 46.8 mm^2 [18], and Iriuchishima et al. 46.9 mm^2 [20]. Differentiating between gender Anderson et al. [3] calculated a cross-sectional area of 44 mm^2 for men and 36.1 mm^2 for women, Dienst et al. [9] of 56.8 mm^2 for men and 40–50% less for women on MRI, and Pujol et al. [33] of 29.2 mm^2 (range 20.0–38.9 mm^2). In the study of Smigielski et al. [45], the calculated cross-sectional area was 52 and 55 mm^2 for women and men, 2 mm close to its femoral insertion site, and 33 and 38 mm^2 at midsubstance, respectively. The mean width at midsubstance was 11.4 mm (range 9.8–13.8) and the mean thickness 3.4 mm (range 1.8–3.9).

Tibial ACL Attachment

The bony tibial ACL attachment is located in the fossa intercondylaris anterior. Until recently, it was described in the literature to be of oval shape, with the insertion of the AM bundle in the anteromedial aspect of the ACL footprint and in direct relationship to the medial tibial spine and the insertion of the PL bundle in the posterolateral aspect close to the lateral tibial spine and in front of the posterior root of the lateral meniscus [7, 10, 11, 13, 15–18, 40]. Many previous investigators divided the tibial insertion site into the footprints of the anteromedial (AM) and posterolateral (PL) bundles or three bundles [2, 4, 7, 10, 11, 13, 15–18, 24, 40, 46].

Recently, Smigielski et al. [44] described the tibial ACL attachment to be "C-shaped." They could not observe any central nor posterolateral bony insertion of the tibial ACL fibers which is the place of the bony insertion of the anterior root of the lateral meniscus. Instead of a PL bundle, they found posteromedial (PM) fibers laterally along the medial tibial spine. In contrast to previous studies describing an "oval" midsubstance, the authors observed a flat and thin appearance of the ACL resembling a "ribbon-like" ligament. This flat ACL midsubstance formed a narrow C-shaped bony attachment along the medial tibial spine to the anterior aspect of the anterior root of the lateral meniscus in the area of intercondylaris anterior. There were no tibial posterolateral inserting ACL fibers but only anteromedial and posteromedial (PM) fibers [42, 45]. Siebold et al. [42] reconfirmed above findings by using calipers (Figs. 2 and 3). Based on their findings they proposed to abandon the term "PL bundle" and use the term "PM fibers" instead according to its tibial attachment.

The ACL "fanned out" beneath the transverse meniscal ligament creating a "duck-foot-like" bony tibial attachment, and a few fascicles of the anterior aspect of the ACL may blend with the anterior attachment of the lateral meniscus

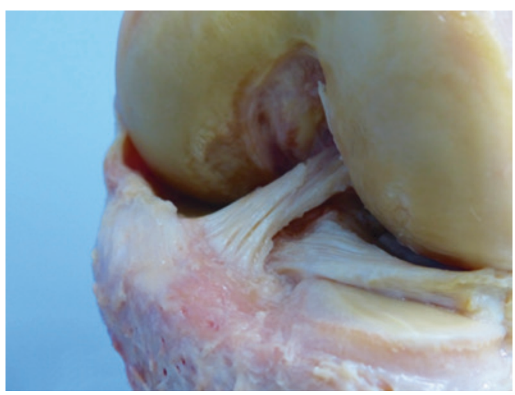

Fig. 2 Left knee with anterior root of lateral meniscus inserting just posterior to tibial ACL attachment in the area intercondylaris anterior

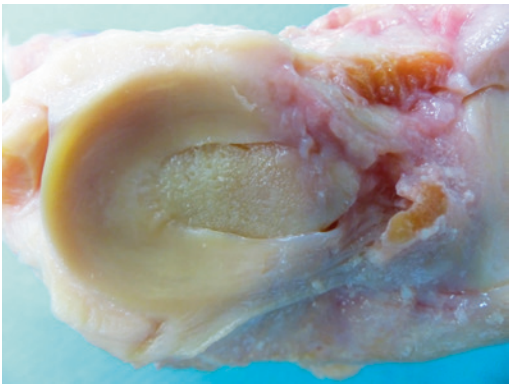

Fig. 3 View onto lateral tibial plateau with lateral meniscus and tibial ACL attachment (right knee) after removal of femur. The most anterior fibers of the anterior root of lateral meniscus are in direct contact with the flat "C"-shaped midsubstance fibers close to the tibial ACL attachment. Anterior root of lateral meniscus just posterior to tibial ACL attachment. The posteromedial ACL attachment is along the medial tibial eminence. No insertion of ACL fibers at the lateral tibial eminence

Fig. 4 The lateral meniscus with its anterior and posterior roots and the tibial ACL attachment with its "C-shaped" midsubstance fibers form a "rain-drop-like" ring around the lateral tibial eminence

as may do some posterior fibers of the ACL with the posterior attachment of the lateral meniscus [4, 42, 45].

Fibers of the anterior and posterior horn of the lateral meniscus blended with the "C"-shaped ACL insertion. Together with the lateral meniscus, the tibial insertion formed a complete "raindrop-like" ring structure (Fig. 4). The root of the lateral meniscus was covered by fat and overpassed by the flat ACL ligament anteriorly. The "C"-shaped ACL attachment had an average length of 13.7 mm (range 11.5–16.1 mm) and an average width of 3.3 mm (range 2.3–3.9 mm). The most anterior part of the "C" had an average length of 8.7 mm (range 7.8–10.5 mm) in the mediolateral direction, and the medial part of the "C" along the medial tibial spine had an average length of 10.8 mm (range 7.6–14.5 mm) in the anteroposterior direction. The most posterior fibers of the "C" along the medial tibial spine were an average of 2.8 mm (range 1.8–3.8 mm) anterior to the medial intercondylar tubercle [4, 42, 45].

The tibial insertion could micros- and macroscopically be divided into a "direct" and "indirect" part. The "direct" insertion was 3.3 mm narrow but 13.7-mm-long C-shaped attachment of the midsubstance fibers, and the "indirect" part was the anterior and broader attachment of the "fan-like" extension fibers, which extended from the midsubstance fibers and broadly spread underneath the transverse ligament toward the anterior rim of the tibial plateau. Both parts together formed a "duckfoot-like" bony footprint of the ACL, which was found by several authors in earlier dissection studies [4, 31, 42, 45].

Dimensions of the Tibia ACL Attachment

There are big variations of the tibial ACL attachment. According to the previous literature, the attachment area was described to be an average of 136 ± 33 mm^2 with the AM footprint between 35 and 77 mm^2 and the PL footprint between 32 and 64 mm^2 [17]. The tibial attachment was described to be approximately 11 mm wide and 17 mm long in the anteroposterior direction [4, 16]. In 2012, Smigielski [44] described the tibial attachment to be "C-shaped" with an average area of the direct part of 34.61 mm^2 (range 22.7–45.0 mm^2) and of the indirect part of 78.7

mm^2 (range 64.5–94.5 mm^2). The whole tibial ACL attachment was in the shape of a "duck-foot-like" bony ACL footprint with a combined area of 113.03 mm^2 (range 85.7–130.7 mm^2). The average AP length of the tibial ACL insertion along the medial tibial spine was 10.8 mm (range 7.6–14.5 mm).

Consequences for ACL Reconstruction

On the femoral side, it may be more anatomical to create a straight flat bone slot on the "direct" insertion of the ACL [37]. However, Mochizuki et al. [25] found that it is very difficult to reconstruct the fan-like "indirect extension fibers" with our current surgical techniques.

On the tibial side, the flat and long C-shaped "direct" attachment of the ACL midsubstance may support a flat footprint reconstruction along the direct attachment line, too. However, a bone tunnel is not ideal to recreate the anatomy and also may damage the bony attachment of the anterior horn of the lateral meniscus. Similar to the femoral side a bone slot may be ideal to reconstruct the "functional" "direct" insertion of the ACL. By creating a "C"-shaped bone slot it may also be possible to spare the bony root of the anterior horn of the lateral meniscus. A posterolateral bone tunnel should be avoided, because it is non-anatomical.

A good approximations of the native ACL would be a flat threefold semitendinosus graft, a double-bundle procedure with two 5–6 mm doubled semitendinosus grafts [1, 4–6, 14, 17, 27, 28, 32, 36, 41, 43], a 10-mm-wide natural (flat)-shaped patella tendon graft [38], or a 10-mm-wide and flat quadriceps tendon graft [14].

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High-Grade Pivot Injuries and Quantitative Evaluation of Degree of Instability

Guan-yang Song and Hua Feng

Abstract

The pivot-shift is the most specific clinical test to assess pathological knee joint rotatory laxity following anterior cruciate ligament (ACL) injury. This chapter attempts to describe the anatomic structures responsible for creating a high-grade pivot-shift and their potential role in customizing ACL reconstruction. A review of the literature demonstrates that disruption of the secondary stabilizers of anterior translation of the lateral compartment including the lateral meniscus, anterolateral capsule, and ilio-tibial band (ITB) contributes to a high-grade pivot-shift in the ACL-deficient knee joint. Additionally, the morphology of the lateral tibial plateau, including increased posterior tibial slope (PTS), can also contribute to high-grade pivot-shift.

Keywords

High grade pivot-shift · ACL · Quantitative evaluation

G. Song · H. Feng (✉)
Sports Medicine Service of Beijing Jishuitan Hospital, No. 31 of Xin jie kou East Street, Xi Cheng District, Beijing, China
e-mail: fenghua20080617@126.com

Introduction

The pivot-shift test evaluates the combined tibio-femoral internal rotation and anterior tibial translation that occurs when the ACL is injured or deficient. The pathological motion elicited in the test is recorded as grade 0—normal, grade I—glide pivot, grade II—a jerk with subluxation or clunk, and grade III—significant clunk with locking (impingement of the posterolateral tibial plateau against the femoral condyle) [7]. Grade II and grade III are often defined as “high-grade pivot-shift” during the clinical practice. The grade of the pivot-shift has been shown to correlate with patient reported functional instability and clinical outcomes as well as the development of osteoarthritis (OA) [8].

The pivot-shift is a complex, multiplanar maneuver that incorporates two main components: translation (the anterior subluxation of the lateral tibial plateau followed by its reduction) and rotation (the rotation of the tibia relative to the femur). Clinically, the magnitude of the pivot-shift is graded in accordance with the subjective feel of the reduction as the anteriorly subluxed tibia reduces during knee flexion. This subluxation/reduction event occurs in the lateral compartment at approximately 20–30 degrees of knee flexion [10].

Several studies have recently focused on deconstructing the pivot-shift into its component elements. It was demonstrated that lateral

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compartment translation correlates well with the clinical grade of the pivot-shift [22]. The presence of the pivot-shift itself may be a key determinant in patient outcome. Identifying the structures responsible for producing a high-grade pivot-shift may allow for patient-specific surgical reconstruction strategies (i.e., single-versus double-bundle ACL reconstruction, extra-articular tenodesis) [16]. In this chapter, we will discuss the structures responsible for a high-grade pivot-shift and its clinical implications for ACL reconstruction.

Key Determinant of the High-Grade Pivot-Shift Test

Since lateral compartment translations are a key determinant of the magnitude of the pivot-shift, it is not surprising that an increase in the grade of the pivot-shift has been noted with injury to the lateral structures in the ACL-deficient knee. The lateral structures that can affect this anterior rotatory laxity include the lateral meniscus, anterolateral complex, and ilio-tibial band (ITB) [18]. Altered lateral compartment anatomy, including an increased posterior tibial slope (PTS) in an ACL-deficient knee [17], has also been shown to contribute to the grade of the pivot-shift test (Table 1).

Role of the lateral meniscus Musahl et al. [13] studied 20 cadaveric knees with a navigation system to track the kinematics of the knee with Lachman and mechanized pivot-shift testing in an intact knee, ACL-deficient knee, and meniscal-deficient knee. After a complete lateral meniscectomy in an ACL-deficient knee, the anterior translation of the lateral compartment increased during the pivot-shift by 6 mm. A complete medial meniscectomy in an ACL-deficient knee, however, did not result in significant increase in lateral compartment anterior translation. The authors concluded that the lateral meniscus was an important secondary stabilizer to rotatory loads in the ACL-deficient knee. Clinically, combined ACL and meniscal injuries are common and frequently involve the posterior horn of the lateral meniscus [1]. These tears are frequently located within the posterior horn, at or near the meniscal root. Recently, Song et al. [19] investigated the risk factors associated with high-grade pivot-shift phenomenon and found clinically that the lateral meniscal tear was an independent risk factor associated with a high-grade pivot-shift test. They further pointed out that the prevalence of posterior lateral meniscal root tears (PLMRTs) was significantly higher in the high-grade pivot-shift group compared with that in the low-grade pivot-shift group, implicating the potential relationship between the presence of PLMRTs and the high-grade pivot-shift phenomenon. Another biomechanical study performed by Shybut et al. [18] demonstrated that a PLMRT would further reduce the rotational stability of the ACL-deficient knee during a simulated pivot-shift loading, emphasizing the contributing role of the combined PLMRT played on the high-grade pivot-shift phenomenon in ACL injuries.

Table 1 Summary of structures and morphological features associated with high-grade pivot-shift tests

	Low-grade pivot-shift	High-grade pivot-shift
Disrupted structures	ACL	ACL+
		1. Lateral meniscus—secondary stabilizer to rotatory loads in the ACL-deficient knee
		2. Anterolateral complex—helps control tibial internal rotation, especially from 20 to 30 degrees of knee flexion
		3. ITB—secondary restraint to anterior tibial translation and internal rotation
Morphological features		Posterior-inferior slope of the tibial plateau—results in increased tibial translation during pivot-shift test

Role of the anterolateral complex Injury to the anterolateral complex has been described as a secondary injury in the setting of ACL deficiency [12]. Hughston et al. [9] described the essential lesion for the pivot-shift at the middle third of the lateral capsular ligament, which he defined as a capsular ligament deep to the ITB. Monaco et al. [12] similarly described the role of the anterolateral femoral tibial ligament (ALFTL) or lateral capsular ligament, in the stability of the knee in a cadaveric study. In assessing anterior tibial translation and rotatory laxity after transecting the ALFTL in an ACL-deficient knee, they found increased rotatory laxity at 30 degrees of knee flexion and a higher grade pivot-shift in all cadavers. The authors suggested that anterolateral capsular injuries may be a secondary injury in ACL-deficient knees causing an increase in the pivot-shift phenomenon.

Recent biomechanical studies have further investigated the anatomy of the so-called “anterolateral ligament (ALL)” [3], and some have speculated that an injury to this structure may significantly contribute to increased rotatory knee laxity [15]. Ferretti et al. [6] investigated the prevalence of anterolateral complex injuries in cases of acute ACL injuries. At the time of ACL reconstruction, the lateral compartment was exposed and injuries were detected. They reported that macroscopic tears of the lateral capsule were clearly identified at surgery in 54 of 60 patients. Notably, 90% of the patients in their study showed high-grade pivot-shift phenomenon pre-operatively. They further showed a positive correlation between the concomitant anterolateral complex lesions and the preoperative high-grade pivot-shift phenomenon. Moreover, another study reported by Song et al. [20] found that the prevalence of ALL abnormality seen on magnetic resonance imaging (MRI) was significantly higher in patients with high-grade pivot-shift phenomenon compared to those with low-grade pivot-shift phenomenon. They concluded that careful assessment and proper treatment of the concomitant anterolateral complex injury should be considered especially in knees with high-grade pivot-shift phenomenon.

Role of the ilio-tibial band (ITB) Several studies have suggested that the ITB plays a role similar to that of the anterolateral complex. Its position directly superficial to the anterolateral capsule would predict that they both serve to limit anterior translation and internal tibial rotation and that injury to either of these structures would increase the magnitude of the pivot-shift examination. Galway et al. [7] supported this concept and considered the development of the pivot-shift phenomenon in an ACL-deficient knee as a result of a secondary injury, that is, he found that sectioning the ITB produced a high-grade pivot-shift in an ACL-deficient knee joint.

Role of the posterior tibial slope (PTS) The morphology of the tibial plateau can influence the magnitude of the pivot-shift. In particular, increased PTS has been shown to correlate with an increase in the magnitude of the pivot-shift phenomenon [14]. Brandon et al. [2] showed an association between posterior slope of the tibia and grade of the pivot-shift. In a study comparing PTS in ACL-deficient knees, they also found that the mean slope in those who demonstrated a high-grade pivot-shift was 11.2 ± 3.8 degrees, compared with a mean of 9.2 ± 3.6 degrees in the low-grade pivot-shift group, suggesting that increased PTS was contributory to a higher grade of pivot-shift phenomenon.

Bony morphology has a direct effect on the magnitude and direction of the intersegmental forces transmitted between the femur and tibia. An increase in the PTS has been shown to be associated with an increase in anterior tibial subluxation after ACL injuries. By using sagittal-plane radiographs of ACL-deficient knees, Dejour and Bonnin [5] reported that patients with a higher PTS experienced a greater amount of anterior tibial translation (ATT) during single-limb stance; specifically, for every 10 degrees increase in the PTS, ATT increased by 6 mm. Giffin et al. [7] and Shelburne et al. [17] obtained similar results when they applied a tibio-femoral joint force to cadaveric knees with a surgically altered PTS. Recently, Song et al. [21] reported that knees with $\geq$6 mm static anterior subluxation of the lateral compartment had a significantly greater degree of PTS than those with <6 mm static anterior subluxation of the lateral compartment after acute non-contact ACL injuries.

It seemed that patients with static anterior tibial subluxation or the presence of a “resting pivot-shift position” after an ACL injury may have a different pathoanatomy of the knee joint. Zuiderbaan et al. [23] demonstrated that this subluxation was associated with changes in the position of notch impingement and that extended notchplasty may be necessary during ACL reconstruction to accommodate the anteriorly subluxated tibial position. In addition, Dejour et al. [4] reported satisfactory results of second revision ACL reconstruction combined with slope decreasing tibial osteotomy on nine patients who had an excessive PTS more than 12 degrees. They pointed out that an excessive PTS contributed significantly to the risk of ACL graft failure and recommended correction of the PTS if it exceeded 12 degrees. It seemed that an increased PTS may lead to an anteriorly subluxated tibial position [11]. These observations raise concerns regarding clinical outcomes after ACLR on patients with an obviously increased PTS, as residual anterior tibial subluxation may lead to ACL graft impingement and residual post-operative pivot-shift phenomenon.

To summarize, the pivot-shift is a complex, multiplanar maneuver that incorporates two main components: translation (the anterior subluxation of the lateral tibial plateau followed by its reduction) and rotation (the rotation of the tibia relative to the femur). ACL deficiency combined with injuries to the secondary stabilizing anterolateral structures must occur in the setting of a high-grade pivot-shift examination to result in appreciable anterior translation of the lateral compartment and internal rotation of the tibia. This can result from associated injuries to the posterior horn of the lateral meniscus, the anterolateral complex, and ITB at certain flexion angles. Secondly, the bony morphology of the lateral tibial plateau, including the PTS may also play an important role in controlling the anterior tibial translation and further producing the high-grade pivot-shift phenomenon.

Cases Shared by the Author

Since there is no evidence-based research summarizing the current available managements of high-grade pivot-shift ACL injuries, some typical cases from our clinical scenarios will be shared below. Moreover, a critical note will also be abstracted at the end of each case.

Scenario 1: ACL Injury Combined with Posterolateral Meniscal Root Tear (PLMRT)

A 29-year-old man suffered from an ACL injury while playing basketball. He had continuing instability and was referred to our hospital 3 months later. Examination under anesthesia showed grade II pivot-shift result. Moreover, an 8 mm side-to-side difference (SSD) was shown on the KT-1000 arthrometer. Arthroscopic exploration further confirmed the diagnosis of complete ACL injury and PLMRT.

Intra-operatively, the displaced posterolateral meniscal root was repaired by the pull-out suture technique (Fig. 1). The pivot-shift test was performed immediately after the PLMRT

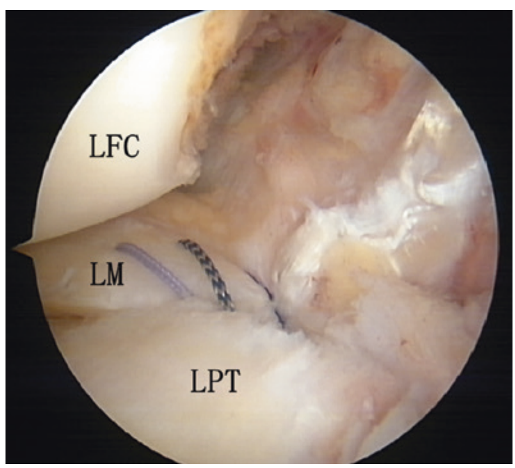

Fig. 1 Arthroscopic image of the repaired posterolateral meniscal root tear, which was repaired by pull-out suture technique. (LFC, lateral femoral condyle; LM, lateral meniscus; LPT, lateral tibial plateau)

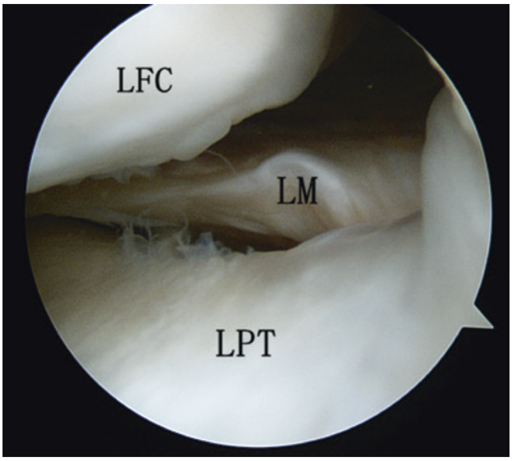

Fig. 2 Second look arthroscopic image of the healed posterolateral meniscal root tear, which showed complete healing result. (LFC, lateral femoral condyle; LM, lateral meniscus; LPT, lateral tibial plateau)

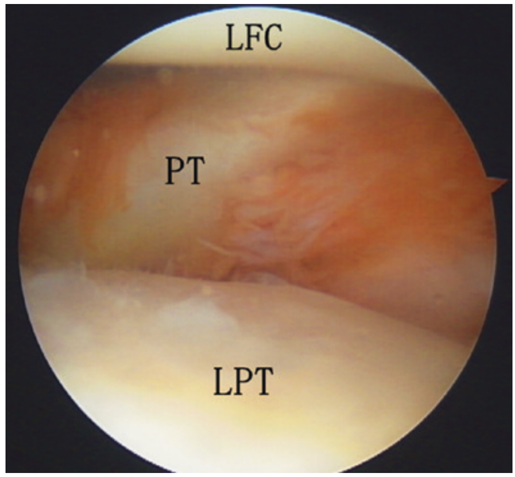

Fig. 3 Arthroscopic image showed deficiency of the posterior horn of the lateral meniscus. (LFC, lateral femoral condyle; PT, popliteal tendon; LPT, lateral tibial plateau)

was repaired and decreased from grade II pre-operatively to grade I. The anatomical ACL reconstruction was then performed using the four-strand hamstring autograft.

At 2-year follow-up visit, the pivot-shift test under anesthesia showed negative result and the side-to-side difference of KT-1000 arthrometer showed 1 mm. The second look arthroscopy showed complete healing of the PLMRT (Fig. 2). The patient successfully returned to his pre-injury level of activity and was very satisfied with the outcome of his surgery.

Critical Note*: Complete PLMRT has been identified to be an independent risk factor of high-grade pivot-shift phenomenon in non-contact ACL injuries. Surgeons should try their best to repair the PLMRT during ACL reconstruction, unless the residual pivot-shift result may be a major concern.*

Scenario 2: Chronic ACL Injury with Posterolateral Meniscal Horn Deficiency

A 26-year-old man suffered from ACL injury while play basketball about 2 years ago. Examination under anesthesia showed grade III pivot-shift result. Moreover, a 9 mm side-to-side difference (SSD) was shown on the KT-1000 arthrometer. Arthroscopic exploration further confirmed the diagnosis of complete ACL injury and chronic deficiency of the posterior horn of the medial meniscus and lateral meniscus (Fig. 3).

Intra-operatively, the extra-articular tenodesis using the ITB was performed (Lemaire technique), aiming to prevent the residual pivot-shift phenomenon (Fig. 4). Result of the pivot-shift test immediately decreased to grade I only after the extra-articular tenodesis procedure was performed. The anatomical ACL reconstruction was then performed using the four-strand hamstring autograft.

At 2-year follow-up visit, the pivot-shift test under anesthesia showed negative result and the side-to-side difference of KT-1000 arthrometer showed 1 mm. The value of lateral tibial translation was decreased to 2 mm compared to 11 mm pre-operatively from the MRI evaluation (Fig. 5). The patient successfully returned to his pre-injury level of activity and was very satisfied with the outcome of his surgery.

Critical Note*: The role of anterolateral complex in controlling pivot-shift phenomenon has been proved by previous studies. However,*

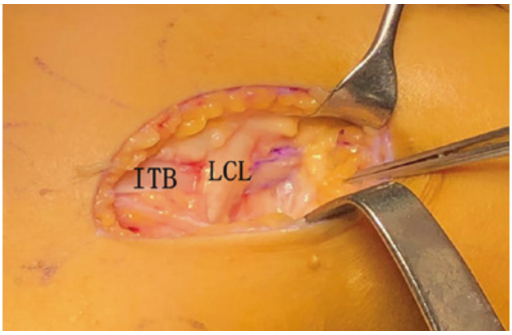

Fig. 4 Surgical photo of the Lemaire technique. (ITB, ilio-tibial band; LCL, lateral collateral ligament)

the diagnosis of anterolateral complex injury on pre-operative MRI is still debatable. We therefore recommend concomitant extra-articular tenodesis on patients with high-grade pivot-shift, especially when the posterior horn of the meniscus was unable to be repaired.

Scenario 3: Chronic ACL Injury with Excessively Increased Posterior Tibial Slope

A 39-year-old man who complained about recurrent knee instability came to our hospital. The MRI showed complete ACL injury and excessive static anterior tibial translation (14 mm) (Fig. 6). Measurement from the lateral X-ray revealed that the posterior tibial slope was 20 degrees (Fig. 7). Examination under anesthesia showed grade III pivot-shift result. Arthroscopic exploration further confirmed the diagnosis of complete ACL injury and chronic deficiency of the posterior horn of the medial meniscus and lateral meniscus.

Concerning about the residual pivot-shift phenomenon and the irreducible static anterior tibial translation, the anatomical ACL reconstruction using the four-strand hamstring autograft and simultaneous anterior closing wedge high tibial osteotomy was performed to correct the abnormally increased posterior tibial slope (Fig. 8).

At 2-year follow-up visit, the pivot-shift test under anesthesia showed negative result and the side-to-side difference of KT-1000 arthrometer showed 1 mm. The posterior tibial slope was decreased to 9 degrees post-operatively. The value of lateral tibial translation was decreased to 1 mm compared to 14 mm pre-operatively from the MRI evaluation (Fig. 6). The patient was very satisfied with the outcome of his surgery.

Critical Note*: The increased posterior tibial slope has been identified as independent risk factor of high-grade pivot-shift phenomenon. In addition, it has been reported that the increased posterior tibial slope is correlated to the increased static anterior tibial translation pre-operatively. During our clinical practice, we performed simultaneous ACL reconstruction and*

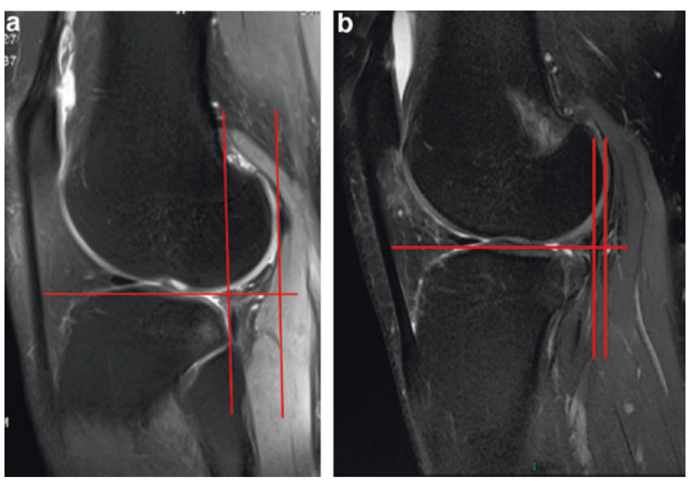

Fig. 5 **a** Pre-operative sagittal MRI image of the anterior tibial translation value was 11 mm; **b** post-operative sagittal MRI image of the anterior tibial translation value was 2 mm at 2-year follow-up visit

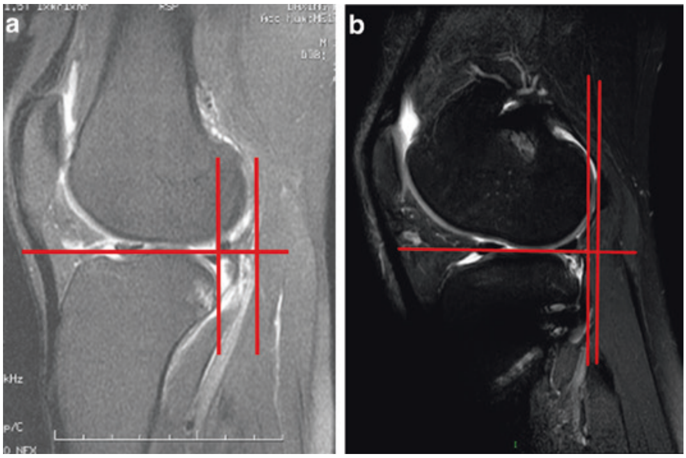

Fig. 6 **a** Pre-operative sagittal MRI image of the anterior tibial translation value was 14 mm; **b** post-operative sagittal MRI image of the anterior tibial translation value was 1 mm at 2-year follow-up visit

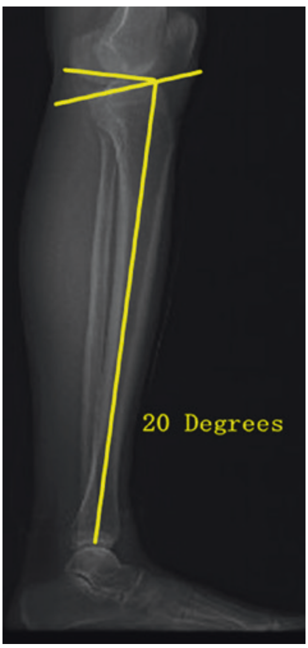

Fig. 7 The pre-operative posterior tibial slope angle was 20 degrees

anterior closing wedge high tibial osteotomy on patients who had high-grade pivot-shift phenomenon, increased posterior tibial slope (more than 15 degrees), and excessive anterior tibial translation (more than 10 mm), aiming to prevent the grafted tendon to be impinged to the femoral notch during the early post-operative period.

Fig. 8 Intra-operative image of the combined anterior closing wedge high tibial osteotomy and the ACL reconstruction

Future Direction in Pivot-Shift Quantification

A quantitative assessment of dynamic rotatory knee laxity due to an ACL injury is difficult to perform in the clinic. The pivot-shift test is a valuable examination maneuver for assessing the rotation and dynamic laxity associated with ACL insufficiency, but it lacks standardization in execution as well as objectivity in grading. Methods to quantitatively assess laxity during performance of the pivot-shift test may improve the value of the test for the diagnosis of ACL injuries and monitoring clinical outcomes.

Quantitatively measuring the pivot-shift began with Noyes et al. [15], who conducted an in vitro assessment of both anterior translation and rotation of the tibial plateau during the pivot-shift examination. Since then, several kinematic measures of the tibial motion during the pivot-shift test such as lateral compartment translation and tibial acceleration have been proposed to quantify measures of the pivot-shift test. Recently, Musahl et al. [14] reported that there was a significant positive association between the clinical pivot-shift grade and quantitative measures of rotatory knee laxity (tibial acceleration and lateral compartment translation) assessed noninvasively by an inertial sensor and an image analysis. They also demonstrated that studying patients with a high grade on the pivot-shift test has significantly increased tibial acceleration and lateral compartment translation compared with those with a low grade. Future direction may focus on applying new techniques for the assessment of the pivot-shift test, which may ultimately help improve the diagnosis and evaluation of outcomes for patients with an ACL injury.

Conclusions

There are several key points when approaching an ACL-injured patient with high-grade pivot-shift phenomenon.

1. Always perform the pivot-shift test under anesthesia both pre-operatively and post-operatively.
2. First check the integrity of the posterolateral meniscal root area. Try your best to repair it when possible.
3. For chronic cases, the posterolateral meniscal root tear may not be repairable. At this time, the extra-articular tenodesis may play an important role in controlling the high-grade pivot-shift phenomenon.
4. The posterior tibial slope should be routinely checked especially for the chronic cases who has excessive anterior tibial translation (>10 mm). The simultaneous anterior closing wedge high tibial osteotomy to correct the abnormal posterior tibial slope (>20 degrees) may be a surgical option, although the long-term clinical outcomes of these combined procedures have not been reported.

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Surgical Techniques of ACL Reconstruction, B. Trans-Tibial Technique

Hyuk-Soo Han and Myung Chul Lee

Abstract

To overcome the disadvantages of classical trans-tibial techniques for ACL reconstruction, a modified trans-tibial technique using quadriceps tendon autograft is introduced. This technique consists of simple maneuvers during the femoral tunnel guide insertion that enable anatomic positioning of the tunnels, and also allows sufficient tunnel length to be obtained for fixation, and the tunnel widening is minimal.

Keywords

ACL reconstruction · Modified trans-tibial technique · Quadriceps autograft · Single bundle

Introduction

A correct femoral tunnel position during intra-articular anterior cruciate ligament (ACL) reconstruction is critical to achieve a successful result. Drilling the femoral tunnel via the tibial tunnel (trans-tibial technique) has been considered the standard technique since the early days of ACL reconstruction and has produced excellent results with various grafts including patellar, hamstring, and quadriceps tendons. However, there were concerns regarding the ability to place the tunnels in anatomic positions because the femoral tunnel position is constrained by the tibial tunnel. Recently, anteromedial portal technique for the femoral tunnel drilling was developed and getting popular. This technique started in response to the transient trend toward double-bundle reconstruction, which necessitated placing one of the tunnels (for posterolateral bundle) far down on the wall of the femoral intercondylar notch, which cannot be done with trans-tibial technique. A meta-analyses comparing long-term results between double- and single-bundle ACL reconstruction have shown no difference in clinical outcome [1]. Morbidity and surgical difficulty have been recognized to be greater with double bundle. Many orthopaedic surgeons have now reverted to anatomic single-bundle reconstruction, placing the femoral tunnel in the middle or middle high of the femoral footprint of ACL, instead at the bottom. Anatomical and biomechanical evidence demonstrated that drilling near the bottom of the femoral wall is unnecessary and indeed not physiologic. Each technique carries its own risks, benefits, advantages, and disadvantages, and there remains no single "gold standard."

H.-S. Han · M. C. Lee (✉)
Seoul National University Hospital,
101 Daehak-Ro Jongno-Gu, Seoul, Republic of Korea
e-mail: leemc@snu.ac.kr

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The advantages of classical trans-tibial techniques are as follows: (1) comfortable knee flexion angle during drilling in natural position of 70–90 degrees, (2) adequate femoral tunnel length, (3) small graft bending angle at the femoral tunnel outlet, and (4) minimal risk of cartilage damage during tunnel preparation. However, classical trans-tibial technique also had a kind of disadvantages. Relatively vertical graft angle (toward 1 or 11 o'clock) was made due to narrow range of divergence from tibial tunnel, which can remain rotatory instability [2]. If tibial tunnel was made in anterior part of footprint, it is difficult to place the femoral tunnel in anatomical position [3]. To overcome these restrictions of trans-tibial technique, several modifications to achieve a more oblique trajectory of the femoral tunnel in the intercondylar notch, such as making the starting point of the tibial tunnel more medial and proximal, were proposed [4–7]. However, there were also other problems like a shorter tibial tunnel and widening of the intra-articular aperture of the tibial tunnel with these modifications. Tunnel characteristics including anatomic position, graft obliquity, and tunnel widening after single-bundle ACL reconstruction performed with use of the modified transtibial technique were not significantly different from those of the anteromedial portal technique or outside-in technique, and clinical results were comparable [8–11].

This chapter introduces a modified trans-tibial technique using quadriceps tendon autograft for single-bundle ACL reconstruction. This technique consists of simple maneuvers during the femoral tunnel guide insertion that enable anatomic positioning of the tunnels, and also allows sufficient tunnel length to be obtained for fixation, and the tunnel widening is minimal.

Surgical Techniques

After anesthesia, a complete physical and arthroscopic examination using standard portals is performed to confirm the ACL rupture and evaluate other intra-articular lesions. Next, all additional procedures are performed before the ACL reconstruction. Following the arthroscopic confirmation of a complete ACL rupture, a quadriceps tendon–patellar bone autograft (QTPB) from the ipsilateral limb is harvested.

Step 1: Harvest QTPB Graft

The QTPB is harvested through a 4–6 cm midline incision centered over the proximal border of the patella (Fig. 1). The graft consists of a proximal patellar bone plug and the central one-third of quadriceps tendon strip. Keeping the knee flexed to 80° facilitates the harvest by maintaining tension on the quadriceps tendon. Parallel proximal cuts using a 10 mm graft harvester are made on the quadriceps tendon to get a 10-mm-wide, 6–7-mm–thick, and 70–80-mm-long strip including the full thickness of the rectus femoris tendon and partial thickness of the vastus intermedius tendon. Next, a 10-mm-wide, 20-mm-long, and 7–8-mm-thick trapezoidal bone block is obtained from the proximal patella using a saw and osteotome in continuity with the quadriceps tendon strip. Care is taken not to enter the suprapatellar pouch by saving parts of the vastus intermedius tendon. If entry

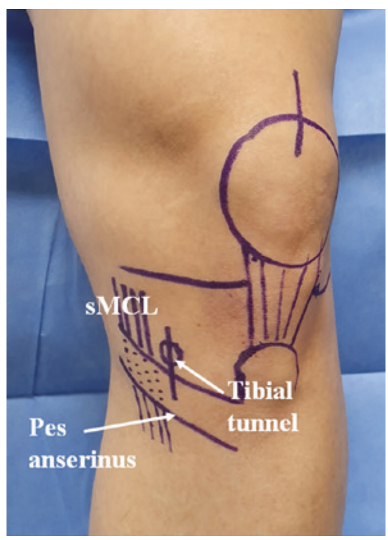

Fig. 1 The incision for quadriceps tendon harvest and the tibial tunnel starting point are marked on the skin. sMCL = superficial medial collateral ligament

occurs, the synovial membrane is repaired with an absorbable suture. The superficial layer of the remaining tendon is closed transversely with absorbable closing sutures. The patellar bone defect is not grafted.

Step 2: Prepare QTPB Graft

The QTPB graft is prepared to allow smooth passage through 10 mm diameter tunnels. The bone plug is trimmed to a bullet shape using a saw and a rongeur. The bone block from proximal patella is perforated transversely with drill, and two absorbable sutures are passed through the transverse holes. The tendinous portion of the graft is secured with thick non-absorbable sutures using Krackow-type stitches leaving approximately 3 cm intra-articular portion (Fig. 2).

Step 3: Create Tibial and Femoral Tunnels

Every effort is made to preserve as much of the ACL remnant as possible during the procedure. However, a remnant may be sacrificed to expose and identify the anatomic insertion sites of the ACL bundles on the femur. In creating the tibial tunnel, the knee is flexed to 90°. A 3 cm longitudinal skin incision is made at the anteromedial side of the proximal tibia. The entry point of the tibial tunnel is created 4–5 cm distal to the medial joint line, 2–3 cm medial to the tibial tuberosity, 1 cm superior to the attachment of the pes anserinus, and just anterior to the superficial medial collateral ligament. Using a tibial drill guide, a guide pin is inserted at an angle of 55° or 60° to the tibial plateau, which is aimed at the central portion of the ACL distal remnant. A 10 mm tibial tunnel is made along the guide pin using a cannulated reamer. To create the femoral tunnel, a 7 mm offset femoral drill guide is directed at the center of the ACL femoral footprint (the lateral bifurcate ridge on the inner wall of the lateral femoral condyle: around the 10:30 clock position on right knee/1:30 clock position on left knee) through the tibial tunnel with the knee flexed to 90° and applying an anterior drawer force to the proximal tibia, a varus force, and an external rotation force to the lower leg (Figs. 3 and 4). If necessary, the femoral aiming guide is rotated laterally to achieve

Fig. 2 Prepared quadriceps tendon graft. The bone block is perforated transversely with drill holes and passed with two absorbable sutures. The tendinous portion is secured with two non-absorbable sutures using Krackow-type stitches

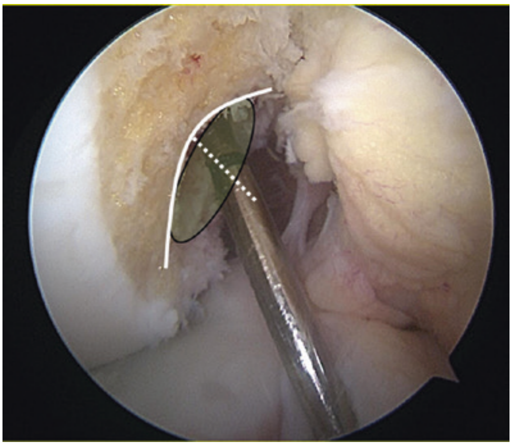

Fig. 3 Arthroscopic view of anatomical femoral tunnel following creation

Fig. 4 Modified transtibial technique maneuver. ① application of an anterior drawer force to the proximal tibia; ② application of an additional varus force to the proximal tibia; ③ application of an additional external rotation force to the proximal tibia and external rotation of the guide

the target femoral position. Applying a varus force to the lower leg, with the thigh fixed to the leg holder, provides lateral opening of the knee joint, which enables to aim the femoral guide to the anatomical footprint. Then, a femoral tunnel guide pin is inserted through the guide and a 10-mm-diameter, 20- or 25-mm-long femoral tunnel is drilled through the tibial tunnel using a cannulated reamer. Next, a slot is made for the screw guide pin on the anterior aspect of the femoral tunnel.

Step 4: Fix the Graft

Secure graft fixation, graft tension during fixation, and graft fixation strength are crucial aspects in ACL reconstruction. Using a Beath pin inserted via the tibial tunnel and through the femoral tunnel, a long looped leading suture is pulled out of the lateral aspect of distal thigh for guiding the passage of graft into the tunnels. The bone block is inserted to the femoral tunnel with the bony part facing forward. A screw guidewire is inserted between the femoral tunnel anterior wall and the cancellous portion of the graft bone plug. Then a metal interference screw is used to fix the bone block with the knee flexed. After graft passage and femoral fixation, pre-tensioning of the graft is performed by flexing and extending the knee through a range of motion. On the tibial side, a screw guidewire is inserted between the tibial tunnel anterior wall and the tendinous portion of the graft. The tendinous part of the graft is firstly fixed with a bioabsorbable screw in the tibial tunnel and is tightened by tying sutures over a bicortical screw, which is inserted 1–2 cm distal to the tibial tunnel with the knee extended. The inserted graft is evaluated arthroscopically to ensure the absence of impingement between the graft and notch in full extension.

Rehabilitation

Immediately after surgery, full extension is achieved, and full flexion is obtained by 6 weeks. A motion-controlled brace set at 0° to 90° is applied for 4 weeks, and then 0° to full flexion for an additional 2 months postoperatively. Partial weight-bearing is permitted for 6 weeks and progressed as tolerated. Full strenuous activity and sports are allowed after 6 months postoperatively, confirming the recovery of quadriceps muscle strength.

Conclusion or Summary

We believe that the modified transtibial technique with quadriceps tendon autograft enabled anatomic positioning of the tunnels and secured sufficient femoral and tibial tunnel length for fixation, while resulting in satisfactory clinical results without critical complications.

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Surgical Techniques of ACL Reconstruction, A. AM Portal Technique

Dong Jin Ryu and Joon Ho Wang

Abstract

By increasingly recognized importance of femoral tunnel position on restoration of native knee kinematics, use of the anteromedial portal (AMP) for establishment of the femoral tunnel is growing interest. The AMP technique is meant to allow for more anatomic femoral tunnel position. To perform easily, appropriate portal formation is the key to the AMP technique. To avoid crowding and jamming of instrument through the AM and additional anteromedial (AAM) portal, it is recommended to make the portals at least 1.5 cm space. The bony anatomy of the lateral femoral condyle is helpful in locating the boundaries of native ACL. Femoral tunnel would be made by using flexible guide and with hyperflexed knee position. Slightly medial positioned tibial tunnel in the native ACL footprint can reduce the risk of graft impingement. After graft passage, the endobutton CL is flipped on the lateral femoral cortex. Before final securing, the position of button should be checked under C-arm fluoroscopy. Finally, the tibial side of graft is secured with bio-absorbable interference screw in full extension with tibiofemoral reduction force. Despite there are the technical challenges associated with AMP technique, complications can be avoided with understanding of the potential pitfalls and technical principles.

Keywords

AM portal technique · Anatomic reconstruction · Flexible guide · Complication

D. J. Ryu · J. H. Wang (✉)
Samsung Medical Center, 81 Irwon-ro, Irwon-dong, Gangnam-gu, Seoul, Republic of Korea
e-mail: mdwang88@gmail.com

Introduction

Femoral tunnel creation during anterior cruciate ligament (ACL) reconstruction has been performed through the previously reamed tibial tunnel. The transtibial (TT) technique, which can lead to the creation of a non-anatomic aperture with vertical femoral tunnel position [1, 2]. By increasingly recognized importance of femoral tunnel position on restoration of native knee kinematics, use of the anteromedial portal (AMP) for establishment of the femoral tunnel is growing clinical and research interest. The AMP technique is meant to allow for more anatomic, lower placement of the femoral tunnel and better re-creation of the native origins of the anteromedial (AM) and posterolateral (PL) bundles on the femoral condyle [3, 4]. The AMP enables the surgeon to visualize and position the femoral tunnel independently of

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the tibial tunnel. However, some studies [5–7] have devaluated the technical challenges and steep learning curve associated with application of the AMP technique. Complications that have been described include poor visualization during reaming, crowding of instrument, short femoral tunnel, posterior wall breakage, iatrogenic chondral damage of medial femoral condyle (MFC), acute graft-tunnel bending angle [8–14]. Despite the risk of above problems, the AMP technique has continued to grow in popularity, and we believe that it would become a standard technique for performing ACL reconstruction.

Here, we describe our approach for ACL reconstruction using AMP technique with a single bundle auto-hamstring graft and suspensory device (EndoButton CL, Smith and Nephew, Andover, Massachusetts) and some technical tips related to avoidance of complications.

Re-physical Exam Under Anesthesia and Position

Following induction of anesthesia, re-physical exam performed for range of motion and ligamentous stability with the Lachman, pivot shift, and anterior and posterior drawer tests and varus and valgus stability at 0 and 30 degrees of flexion. A tourniquet is placed high on the thigh, and the patient is positioned for lithotomy on the operating table. Following the setting of position, check the availability of the hyperflexed knee (Fig. 1). After applying arthroscopic surgical draping, the tourniquet is inflated after the limb is exsanguinated.

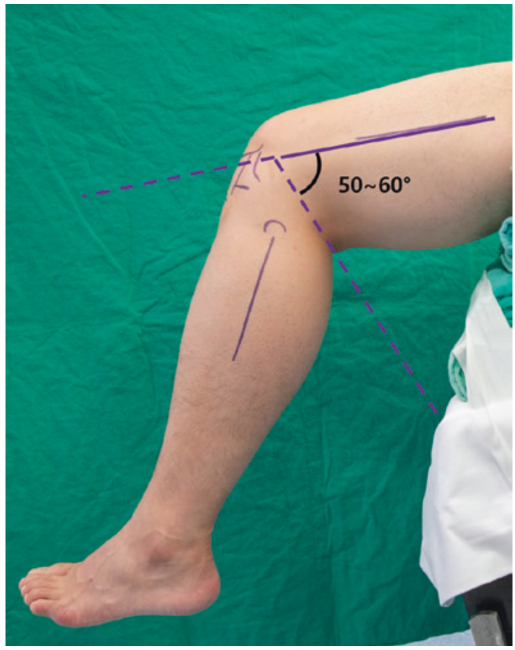

Fig. 1 A tourniquet is placed high on the thigh, and the patient is positioned to lithotomy on the operating table. Following the setting of position, check the availability of the hyperflexed knee

Portal Formation

As with other arthroscopic procedures, proper portal formation is the key of the AMP technique. Well-positioned portal will provide good visibility and ease of operation of the instrument, but incorrect positioning can make surgery difficult. For anatomic ACL reconstruction using AMP technique, it has advantages to form portal that allows easy viewing of anatomical landmarks. To view easily, superior and medial located AL portal formation is recommended (Fig. 2a). A high AL portal is important to avoid poor visualization [5, 15]. With the knee flexed 30 degrees, the AL portal is formed first using No. 11 blade and straight hemostat, just lateral to the patellar tendon and superior to the inferior pole of the patella to avoid the infrapatellar fat pad [15]. This high AL portal could facilitate viewing tibial footprint.

The AM portal is formed under direct visualization using 18G-spinal needle. The AM portal is formed along the medial border of patellar tendon and upper articular line of medial meniscus, taking care not to injure the intermeniscal ligament. Following the formation of AM portal, the shaver is introduced and debride some of the fat pad and ligamentum mucosum to facilitate visualization. During AMP technique, the AM portal is used for viewing portal. The additional anteromedial (AAM) portal is formed at the level of the joint line, medial to the AM portal with transverse incision. To avoid crowding and jamming of instrument through the AM

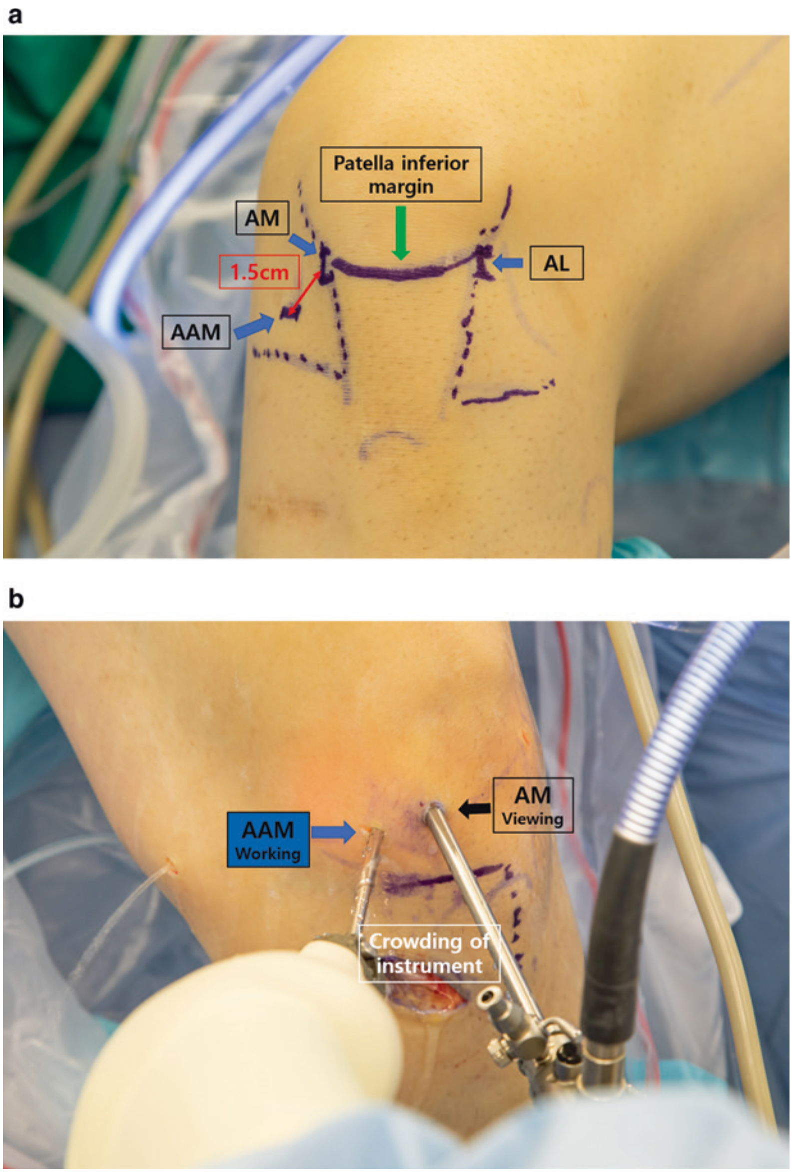

Fig. 2 **a** Superior and medial located AL portal is recommended. The AM portal is formed along the medial border of patellar tendon and upper articular line of medial meniscus. The additional anteromedial (AAM) portal is formed at the level of the joint line, medial to the AM portal with transverse incision. To avoid crowding and jamming of instrument through the AM and AAM portal, it is recommended to make the portals at least 1.5 cm space. **b** During AMP technique, the AAM portal is used for working portal

and AAM portal, it is recommended to make the portals at least 1.5 cm space (Fig. 2a). The 18G-spinal needle should pass safely above the medial meniscus and reach the center of the femoral ACL footprint with enough space. It can allow safe for using instruments without damage to the medial femoral condyle (MFC) as femoral tunnel drilling. After AAM portal formation, the shaver is reintroduced and debride fat pad more to facilitate the passage and manipulation of the instrument. During AMP technique, the AAM portal is used for working portal (Fig. 2b).

Auto-hamstring Tendon Harvest and Graft Preparation

Mark at distal 5 cm from the knee joint line and 2 cm medial from the Patella tendon center. After palpating Semitendinous and Gracilis tendon as you can, make a 4–5 cm sized oblique-transverse incision along the skin crease. Oblique-transverse incision can reduce the risk of injury infrapatellar branch of the saphenous nerve [16]. Following re-palpation of Gracilis and Semitendinous tendon, lifting the sartorial fascia with forcep and dissecting to proximal portion. In this process, it is often attached with Gracilis and sartorial fascia, pre-detach them carefully using metzenbaum. Until both of the Gracilis and Semitendinous tendons are clearly and separately identified, neither tendon should be harvested.

The Gracilis tendon, being more proximal and having acute angle, can be hooked out of the subsartorial space with a right-angled forcep and is harvested first (Fig. 3a). Although Gracilis rarely has any significant vinculi, identify and detach all of its vinculi using finger and metzenbaum before the harvest [17]. The tendon stripper applied to the tendon should be passed beyond the proximal tibia and the graft is amputated from its muscular attachment at this length.

After the harvest of the Gracilis tendon, the semitendinosus tendon is thus exposed and care to identify all of its vinculi to prevent short harvest of the tendon (Fig. 3b). The vinculi pass distally and medially from the body of the tendon toward the medial gastrocnemius [18]. The vinculi can be hooked and pulled out of the wound or divided distal to the tendon. Following the confirmation of all of the vinculi dissected, the tendon stripper is applied. After insertion of negative pressure drain to prevent hematoma formation at graft site, sartorial fascia would be repaired by absorbable suture No 2-0.

Muscle and fat tissue are cleanly removed from the graft tendons. After folded twice the graft, check the diameter and length of the graft. No. 5 non-absorbable whipstitch leading sutures applied to tibial insertion side and then whipstitched using a no. 2 Vicryl absorbable suture over a length of 40 mm to form a four-stranded bundle [17]. No. 1 Vicryl is then used to suture 10 mm of tendon on the looped femoral end, which is then measured diameter finally. A surgical pen is used to mark the position (femoral tunnel length) from the end of the graft. And additional mark is made at distal 7 mm from the previous marking which indicates the degree of the pass during the graft passing. The graft is left wrapped in saline-soaked gauze until it is passed through the joint (Fig. 4).

Femoral Tunnel Preparation

When forming a femoral tunnel, the viewing portal uses an AM portal and the working portal uses an AAM portal. Without for femoral

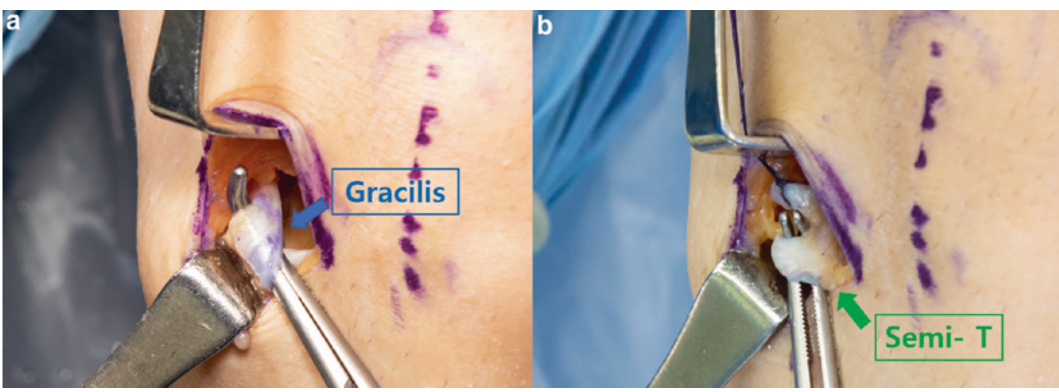

Fig. 3 **a** The Gracilis tendon, being more proximal and having acute angle, can be hooked out of the subsartorial space with a right-angled forcep and is harvested first. **b** After the harvest of the Gracilis tendon, the semitendinosus tendon is thus exposed

Fig. 4 Final preparation of auto gracilis and semitendinous tendon

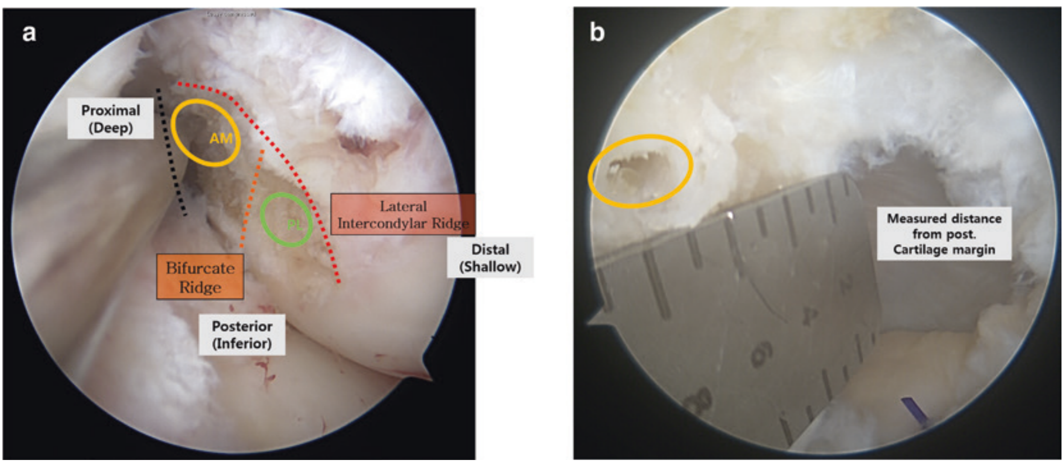

Fig. 5 **a** The anatomical footprint of femur (left side knee) viewing from AM portal. **b** For single bundle reconstruction, the center point located at 3 mm inferior to roof, 7 or 8 mm from posterior cartilage margin (view from AM portal, right side knee)

tunnel formation, the knee maintains 90 degrees flexion during preparation. It's critical to see the anatomic ACL femoral side attachment correctly, using a radiofrequency thermal device to carefully remove any remaining tissue. The bony anatomy of the lateral femoral condyle is helpful in locating the boundaries of native ACL (Anterior: lateral intercondylar ridge, Posterior: inferior cartilage margin of lateral femoral condyle, Proximal: posterior cartilage margin, Distal: distal cartilage margin) (Fig. 5a). Lateral bifurcate ridge is a landmark to distinguish between AM bundle and PL bundle attachment. After identifying footprints, the length and width of the ACL insertion sites are measured with arthroscopic metal ruler. In our experience, the length of ACL footprint measures from 22 to 24 mm from posterior cartilage margin to anterior margin. For single bundle reconstruction, the center point located at 3 mm inferior to roof, 7 or 8 mm from posterior cartilage margin. After confirming the position, footprint marking made using 45-degree angled microfracture awl.

Recheck the marked point again with a metal ruler if it is correctly positioned (Fig. 5b). Next, a flexible guide (Clancy 42 degrees guide (Fig. 6) [19], and guide pin are engaged just a little to fix the point through the AAM portal to the marked center of point. Then, the knee must be hyperflexed to 120 degrees to allow the trajectory of the guidewire directly into the center of the femoral footprint (Fig. 7) [14, 20, 21]. Alternatively, flexible guide pins and reamers have been introduced in an effort to avoid the need for hyperflexion, minimize articular cartilage damage on the MFC, and allow the length of the femoral tunnel to be maximized via a more proximally directed orientation [22]. Following with the knee in hyperflexion (flexible guide: 120 degrees flexion, rigid guide: 135 degrees flexion), the guide pin is advanced through the lateral femoral cortex and the skin. The length of the femoral tunnel is measured through indirect method. The ideal tunnel length is 30–40 mm, and enough length (8 mm) can be left to allow the button to flip.

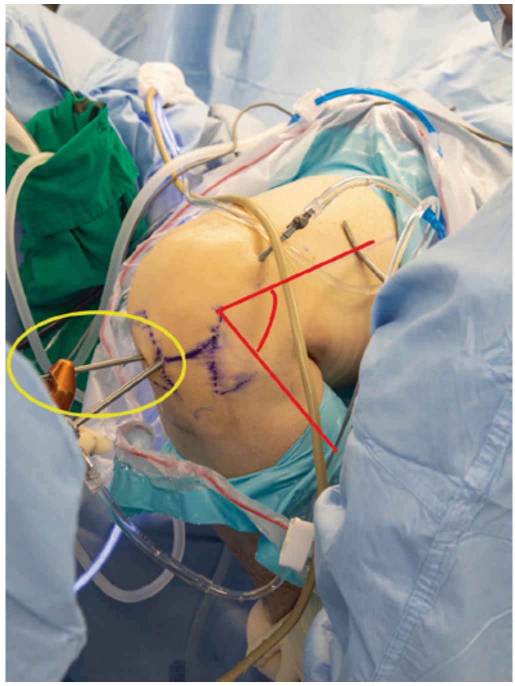

Fig. 7 The knee must be flexed to 120 degrees to allow the trajectory of the guidewire directly into the center of the femoral footprint. This position should be maintained during the formation of the femur tunnel

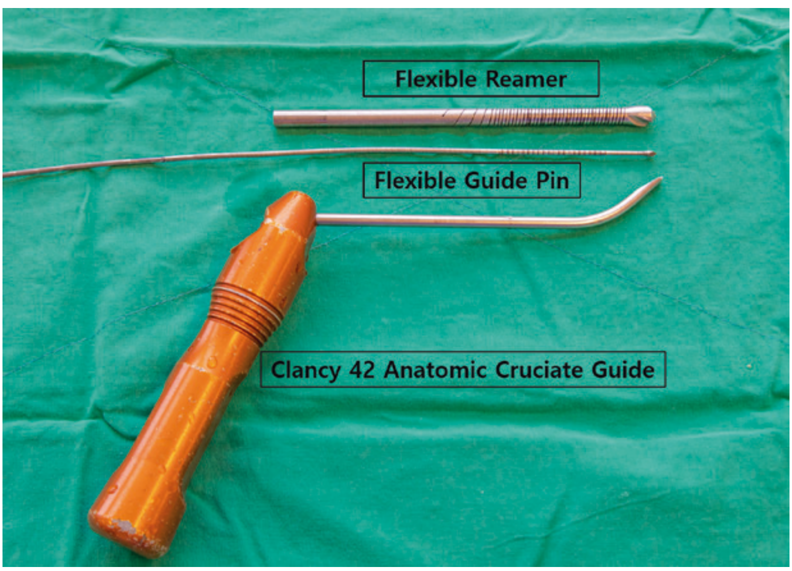

Fig. 6 Flexible guide (Clancy 42 degrees anatomic cruciate guide), flexible guide pin, and flexible reamer set

Provided the angle of knee flexion is maintained, the reamer is then advanced to the appropriate depth taking care to avoid damage to the MFC cartilage by the edges of the reamer. When reaming, use the irrigation tube to remove bone debris while keep the sight. When removing the reamer, pull it out by hand at near around the entrance of the tunnel to reduce the risk of MFC cartilage injury. When using a Sentinel® rigid reamer, should be careful during introducing or removing so that the arrow towards lateral side [14].

Following the tunnel reaming, the endobutton reamer advanced to the lateral femoral cortex. After the guide pin and endobutton reamer unit is removed, check tunnel position and the adequacy of the posterior wall (Fig. 8). Measure the tunnel length directly again using arthroscopic depth. The shaver is introduced to the femoral tunnel area and debride bony debris with the knee 90 degrees flexion.

Tibial Tunnel Preparation

With AL portal viewing, the tibial footprint is measured. The tibial footprint is located between 6 and 7 mm posterior of the ACL ridge and 5 mm lateral from the medial tibial spine. This places the tibial aperture medial in the native ACL footprint (Fig. 9). It can reduce the risk of graft impingement [23]. Furthermore, this medial placement of tibial tunnel creates an obliquity in the coronal plane and reported better rotatory instability [24]. We prefer to preserve the soft tissues around tibial footprint to promote graft incorporation and tibial tunnel widening. After marking the tibial footprint

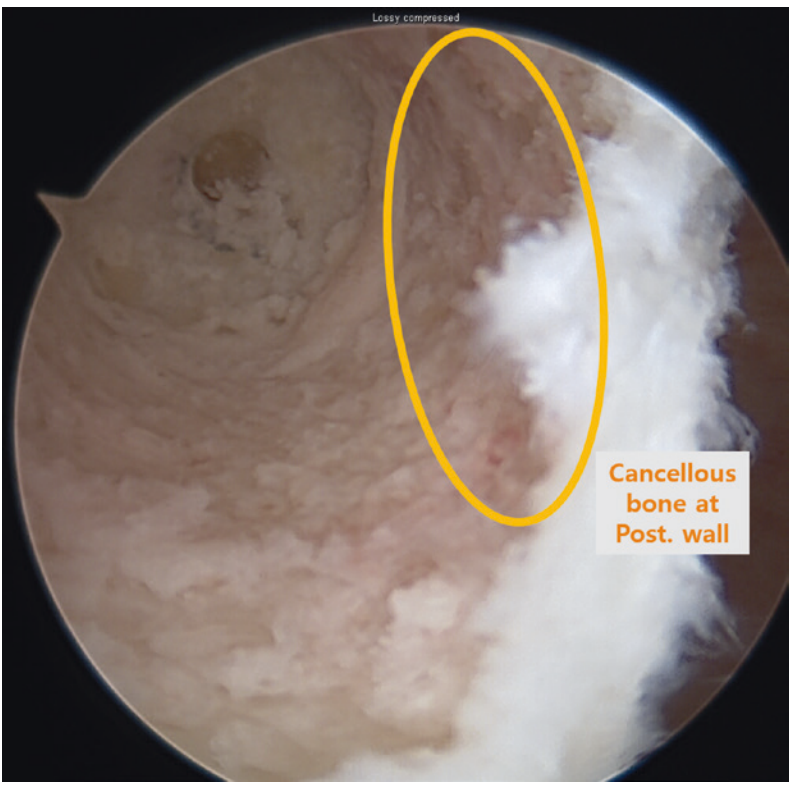

Fig. 8 Check tunnel position and the adequacy of the posterior wall. If you see a cancellous bone fragment (yellow circle) on the posterior wall, it can be judged that there is no blow out fracture has occurred. (viewing from AM portal, right side knee)

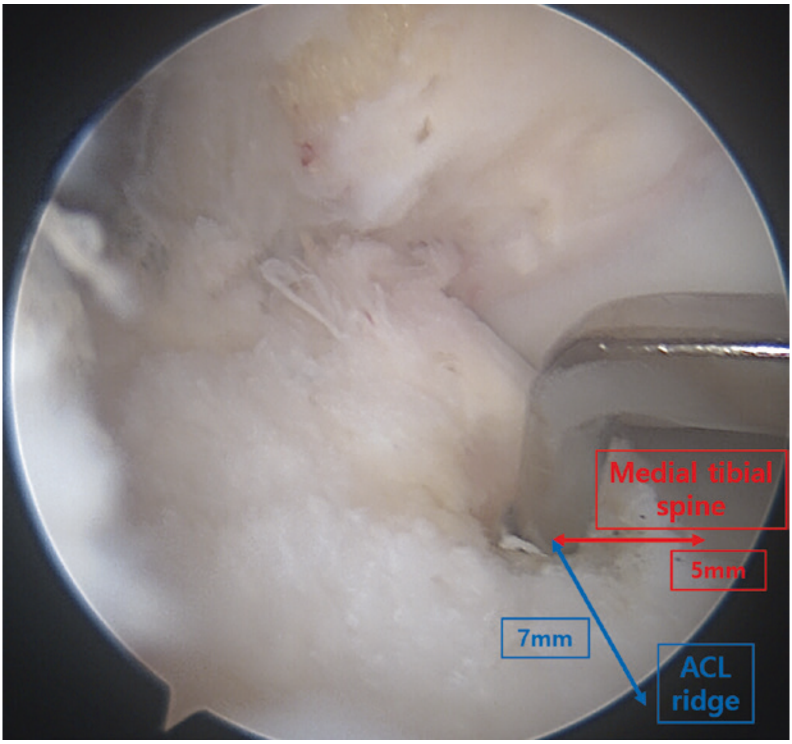

Fig. 9 The tibial footprint is located between 6 and 7 mm posterior of the ACL ridge and 5 mm lateral from the medial tibial spine. (viewing from AL portal, right side knee)

using microfracture awl, the ACL tibial guide zig is introduced through AAM portal. The ACL tibial guide usually set to 50 or 55 degree for single bundle reconstruction.

If auto-hamstring tendon were harvested, the same incision is used for tibial tunnel. If not, 2 cm longitudinal incision is made from the entry marking point. In general, the Pes anserinus superior border is set as the starting point, which can secure a tibial tunnel length of about 30–40 mm. Then, the guide pin is advanced while checking the progress axis. After the guide pin is appropriately positioned, the knee is taken to full extension slowly to ensure whether there would be no graft impingement. A notchplasty is performed only if there is a risk of anterior impingement during flexion and extension motion.

Following standard tibial tunnel reaming, the shaver is introduced to tibial tunnel and debride the bony debris. After the preparation of both side tunnel, a beath pin with a looped suture attached is passed through the AAM portal first, then the knee in the same degree of hyperflexion that was used during femoral tunnel formation (flexible reamer: 120 degrees, rigid reamer: 135 degrees). Following the pin is passed through the skin of the anterolateral thigh, looped suture is pulled through a tibia tunnel using a suture retriever.

Graft Passage and Fixation

Following the femoral side graft anchored to the loop, the beath pin and suture loop retrieved to anterolateral side of thigh. The graft is passed through the femoral tunnel with arthroscopic guide, and the endobutton CL is flipped on the lateral femoral cortex. After flipping the button, pull the graft end of the tibia towards the distal side to check if it is correctly positioned. With holding tension on the distal end of graft, the knee is fully extended to confirm that there is no impingement. The knee is cycled 20 times while still holding tension on the distal end of graft. We finally confirm the position of button under C-arm fluoroscopy. The tibial side of graft is secured with bio-absorbable interference screw in full extension with tibiofemoral reduction force. After a Lachman test is performed to confirm stability. Arthroscopic exam is again performed to check graft position, tension and the knee is examined through full range of motion (Fig. 10). Finally, additional fixation is applied using cortical screw and washer at 1.5 cm inferior of tibial tunnel. The wounds are copiously irrigated especially for tibial tunnel area and closed. The knee is then compressed by elastic bandage and applied cylinder splint in knee extension position.

Discussion

The AMP technique allows the femoral and tibial tunnels to be made independently. It has advantages of allowing more anatomic placement of the graft within the native ACL footprints comparing with TT procedure. It remains to be seen whether the acute angle formed at the graft entrance to the femoral creates a “killer turn” that can lead to long-term graft damage. Despite the technical challenges associated with its use, complications can be avoided with understanding of the potential pitfalls and technical principles. Critical to success with AMP techniques are (1) appropriate AAM portal placement, (2) introduction and advancement of instruments into the joint and notch under arthroscopic visualization, (3) understanding of native footprint anatomy, (4) experience with appropriate flexion and hyperflexion angles of the knee, (5) appropriate graft and tunnel length [25].

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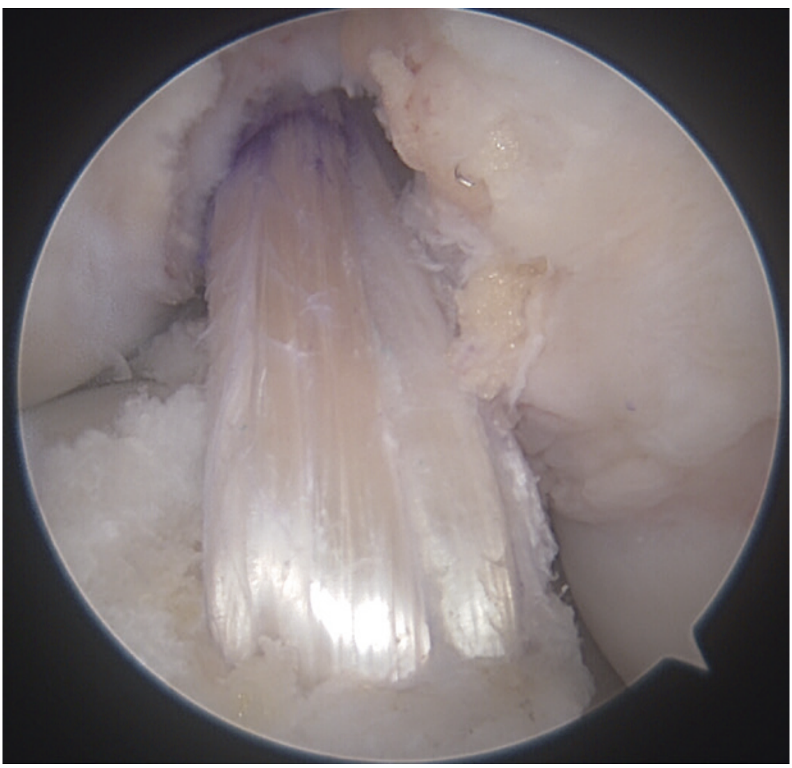

Fig. 10 Finally, arthroscopic exam is performed again to check graft position, tension. (viewing from AM portal, right side knee)

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Surgical Techniques of Anterior Cruciate Ligament (ACL) Reconstruction, C. Outside-in with Remnant Preservation Technique

Jong Min Kim and Jin Goo Kim

Abstract

Outside-in technique is used popular nowadays as tibia tunnel-independent techniques ACL reconstruction along with transportal technique. Moreover, outside-in technique facilitates placement of the femoral tunnel in a center of the anatomic femoral origin of ACL. Recently, there has been growing interest in the substantial roles of the remnant of the ACL after a tear and attempts have been made to preserve remnant of the ACL after a tear. Among them, outside-in technique seems to be a more reliable and precise technique to achieve anatomic femoral origin of ACL with preserving the remnant bundle. In this chapter, the surgical technique and outcomes of ACL reconstruction using outside-in technique with/without remnant preservation are reviewed.

Keywords

ACL · Outside-in · Remnant preservation

Introduction

During the 1980s, arthroscopic ACL reconstruction was performed with an outside-in technique (2-incision technique) which one incision was done for drilling the tibial bone tunnel and the other incision was done for drilling the femoral bone tunnel. The femoral incision was localized posterior to the lateral femoral condyle and drilling was performed using a guide, creating the bone tunnel from outside of the femoral condyle into the knee joint [1]. In this technique, the graft was fixed to the femur from outside to inside the joint by direct visualization [2]. Over time, inside-out arthroscopic techniques (1-incision techniques) for drilling the femoral tunnel were developed because the techniques eliminated the need for the femoral incision [3]. At 2000s, new outside-in drilling techniques with retrograde cutting bits (FlipCutter, Arthrex, Naples, FL) that require only a portal-sized stab wound rather than a lateral incision with dissection were developed [4]. After that, outside-in technique with retrograde drilling has become one of primary techniques in arthroscopic ACL reconstruction [5].

During ACL reconstruction, a remnant of the ACL after a tear could be observed and, traditionally, the remnant had been removed to create the correct tunnels and to decrease the risk of cyclops lesions. However, recently, there has been increasing interest in roles of the remnant

J. M. kim · J. G. Kim (✉)
Orthopedic Department, Hanyang University, Myong Ji Hospital, 55, Hasu-ro 14 beon-gil, Deogyang-gu, Goyang-si, Gyeonggi-do 10475, Republic of Korea
e-mail: jgkim@mjh.or.kr; boram107@daum.net

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as mechanoreceptor and reported for the remnant preservation techniques [6–8]. The outside-in techniques seem to be a more reliable and precise way to achieve an anatomic ACL reconstruction in addition to being helpful in preserving the remnant [6]. Therefore, in this chapter, surgical technique, clinical result, strengths, and weaknesses of outside-in with retrograde drilling technique with remnant preservation are described.

Theoretical Backgrounds of the Remnant Preservation

Theoretically, remnant preservation allows native tissue to grow into the graft which has a positive effect on function and graft integration. Since the first identification of mechanoreceptors in ACL specimens by the Schultz et al. in 1984 [9], several studies have found the distribution of mechanoreceptors to be concentrated around the femoral and tibial attachment sites of the ACL. These receptors are located in subsynovial layer, alongside blood vessels. Due to the peripheral location of the mechanoreceptors, ACL reconstruction through the center of the remnant may preserve these receptors [10]. These receptors play an important role in the complicated neural network of proprioception. Proprioception is a specialized sensory modality that has three functions; a static awareness of joint position, detection of joint movement and acceleration, and efferent activity regulating reflex muscle contractions [11].

ACL tear does not heal spontaneously after injury because of poor vascularization of the torn ligament. However, intrinsic healing potential of ACL has been reported. CD34+ cells, which have potential for high proliferation, self-renewal, and multipotent differentiation capacity, were found in a remnant of ACL tissues [12, 13]. In animal studies, this ACL-derived CD34+ cells contributed to tendon-bone healing and reduction of tunnel enlargement through angiogenesis and osteogenesis [14, 15].

Outside-in Technique for ACL Reconstruction

A routine arthroscopic examination is performed using an anterolateral (AL) portal with a 30° arthroscope. The AL portal is made at the just lateral to patellar tendon and as proximal as possible at inferior tip of the patella [3, 16]. After identifying the status of ACL, an anteromedial (AM) portal is made at the same level as the AL portal, between medial border of patellar tendon and medial femoral condyle [17]. Through the AM portal, the femoral attachment is debrided to identify the anatomical positions of the lateral intercondylar ridge (resident's ridge) and the bifurcate ridge which separates the anteromedial (AM) and posterolateral (PL) bundles [8].

Preparation of the Anatomic Femoral Tunnel

The area of the native femoral-side footprint of ACL is determined by bony landmarks such as the lateral intercondylar ridge (resident's ridge) and posterior cartilage border on the medial wall of lateral femoral condyle. The center of the femoral-side insertion of ACL is determined in reference to the area defined above and the center of the lateral bifurcate ridge or 4–5 cm anterior-distal area of the posterior-proximal margin of the ACL femoral footprint. A microfracture awl is placed through the AM portal with the 30° arthroscope in the AL portal, just above and the center of the lateral bifurcate ridge, to create the femoral pilot hole at about 90° knee flexion when single-bundle reconstruction is planned (Fig. 1a) [6, 18–21]. Next, 30° arthroscope is inserted through the AM portal, and the pilot hole marked by microfracture awl is evaluated before insertion of the FlipCutter guide (Fig. 1b). If the pilot hole is suboptimal, it can be manipulated to the optimal location by inserting the FlipCutter guide (Arthrex, Naples, FL) tip through the AL portal (Fig. 1c).

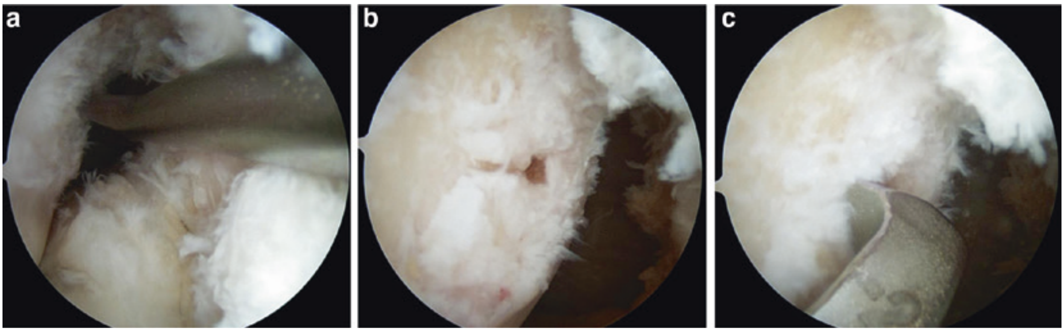

Fig. 1 Arthroscopic images of patient who underwent anterior cruciate ligament (ACL) reconstruction for right knee. **a** A microfracture awl is placed through the anteromedial (AM) portal with the 30° arthroscope in the anterolateral (AL) portal to create the femoral pilot hole. **b** The 30° arthroscope is inserted through the AM portal and the pilot hole is evaluated. **c** The pilot hole is suboptimal, therefore, the FlipCutter guide tip is placed just anterior of the pilot hole

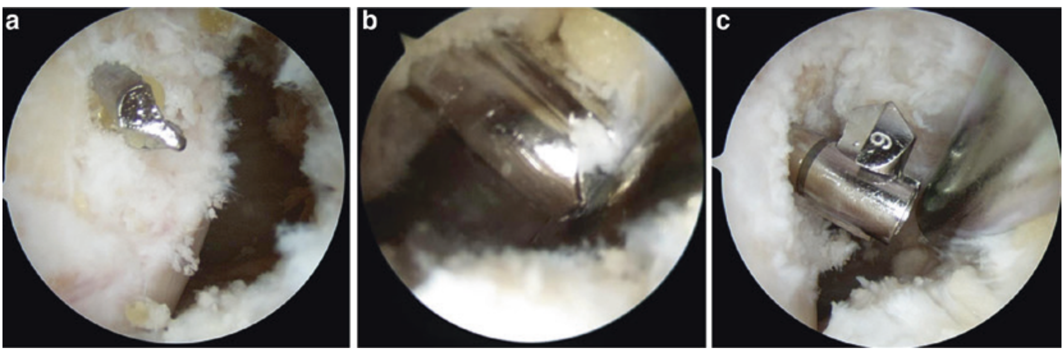

Fig. 2 Arthroscopic images of patient who underwent anterior cruciate ligament (ACL) reconstruction for right knee. **a** The guide pin (2.8 mm) is inserted through the sleeve of the FlipCutter guide from outside to inside direction and the guide is removed. **b** Reaming (4.5 mm) before insertion of the Flipcutter. **c** The FlipCutter is inserted from outside to inside direction. In this patient, the diameter of the graft is 9 mm. Next, make a femoral tunnel in a retrograde manner

The stab incision is made at proximal to the lateral epicondyle and the iliotibial band is divided in line with the skin incision [3, 18]. A sleeve of the FlipCuter guide is positioned in the just anterior and proximal to the lateral epicondyle [22]. The ideal angle of insertion of guide pin is set to 60° to a line perpendicular to the femoral anatomical axis, and 20° to the transepicondylar axis [23]. The guide pin (2.8 mm) is inserted through the sleeve of the FlipCutter guide from outside to inside direction and the guide is removed. Check the position of distal guide tip through the AM portal with the 30° arthroscope (Fig. 2a). Next, the FlipCutter is inserted that matched the diameter of the graft. Make the femoral tunnel in retrograde manner. However, this sequence results in unexpected position of the femoral tunnel, not uncommonly. Reaming (4.5 mm) through the guide pin (2.8 mm) before the FlipCutter insertion is recommended. The 30° arthroscope is inserted through the AL portal and a curette is inserted through the AM portal. Reamer is inserted through the guide pin and reaming is done during the reamer tip is protected by the curette (Fig. 2b). And then, the FlipCutter is inserted and the blade of FlipCutter is rotated 90° into the cutting position using a curette or probe (Fig. 2c). Make a femoral tunnel in a retrograde manner as long as possible (Fig. 3). Occasionally, small patients may have a length of the femoral tunnel less than 25 mm. During the retrograde reaming, remove bone debris through the suction canal inserted through the

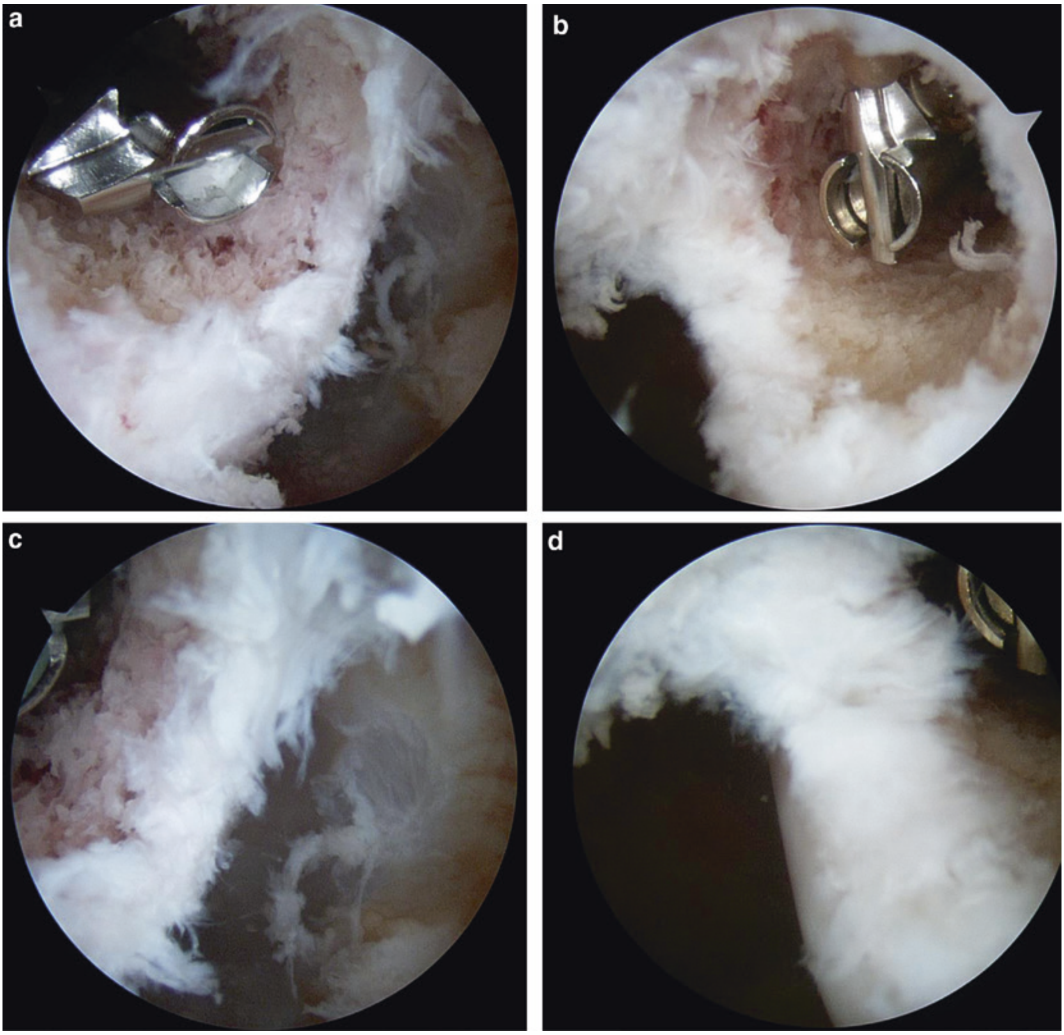

Fig. 3 Arthroscopic images of the femoral tunnels. **a** Right knee. **b** Left knee. **c**, **d** Check a posterior wall thickness of the femoral tunnel through the 30° arthroscope inserted in an anteromedial portal

AM portal. The FlipCutter is removed after the blade tip is straightened and guide wire for graft passage is inserted from outside to inside through the femoral tunnel (Fig. 4).

Preparation of the Anatomic Tibial Tunnel

For tibial tunneling, a commercially available ACL guide is inserted through the AM portal. A tip of the ACL guide is located at center of the tibial-side footprint of ACL at which the midline of the medial and lateral tibial spines intersects with the midline between the posterior border of the anterior horn of the medial meniscus and the lateral meniscus, with the 30° arthroscope through the AL portal (Fig. 5) [20, 22, 24]. Many studies have been reported that various anatomic reference landmarks, including the center are 7 to 8 mm anterior to the anterior margin of the posterior cruciate ligament (PCL) [25], transverse ligament coincides with the anterior edge of the ACL tibial footprint in sagittal plane [26], the center is 9.1 ± 1.5 mm posterior to the transverse ligament and 5.7 ± 1.1 mm

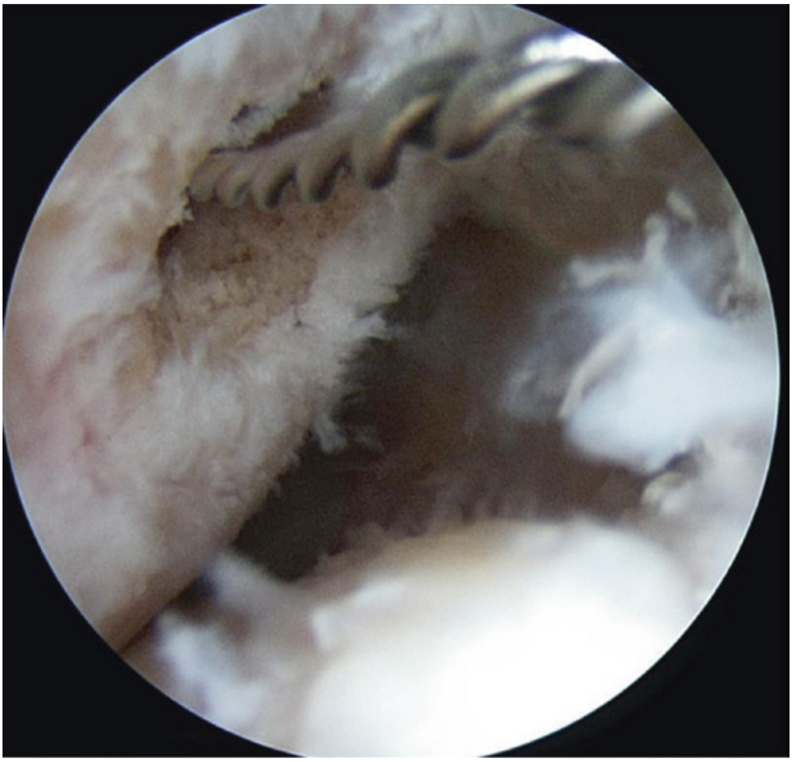

Fig. 4 Arthroscopic image of the guide wire for graft passage. The guide wire is inserted through the femoral tunnel from outside to inside direction

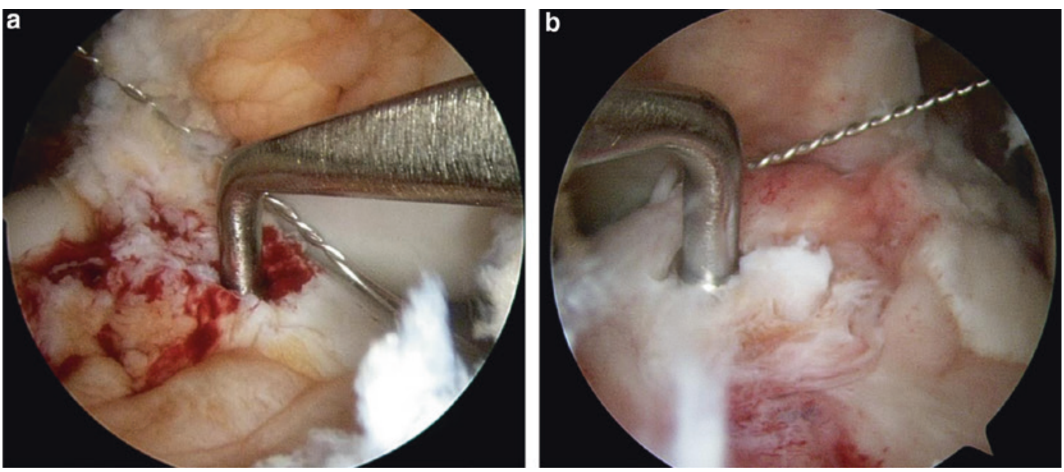

Fig. 5 Arthroscopic images of the anterior cruciate ligament (ACL) guide placement. A tip of the ACL guide is inserted through the anteromedial portal and located at center of the tibial-side footprint of ACL. **a** Right knee. **b** Left knee

anterior from medial tibial eminence [27], and the anterior ridge approximately corresponds to the anterior boundary, the anterior horn of the lateral meniscus to the lateral boundary, and the anterior border of the medial and lateral tibial spines to the posterior boundary [28].

The ACL guide is set 45° to 55° and a guide pin is inserted from the proximal medial tibial condyle to the center of the tibial-side footprint of ACL [6, 18, 21]. The guide pin is placed about 1 cm above the pes anserinus, in front of the medial collateral ligament, and about 1.5 cm posteromedial from the medial margin of tibial tubercle [18, 25]. The tibial tunnel is created to match the graft in diameter, using an expansion reamer. During making the tibial tunnel, a curette is inserted through the AM portal and reamer tip is protected by the curette. After cleaning of the tibial tunnel performed using the shaver, the guide wire for graft passage inserted from outside to inside through the femoral tunnel is pulled out from inside to outside through the tibial tunnel using a suture grasping forceps (Fig. 6).

Graft Passage and Fixation

The graft sutures are passed through loop of the guide wire outside the tibial tunnel and pulled back from the tibial tunnel to the femoral tunnel. The graft sutures are pulled driving the graft from the tibial tunnel to the femoral tunnel.

There are options for fixation of the femoral tunnel such as an interference screw [3, 22] and cortical suspensory buttons [6, 18, 20, 21, 29]. When cortical suspensory buttons are used, the button is flipping and compressing the lateral cortex of femur. Once the complete flipping is done, distal pulling is performed. On the tibial side, an interference screw is used for fixation, and the fixation is augmented by ligating the excess of the graft around the spiked washer and screw at 10° to 15° of knee flexion [30]. When the interference screw is inserted, excessive force should be avoided as the screw may be inserted out of the tibial tunnel (Fig. 7).

A Remnant of the ACL Preservation

During the ACL reconstruction, an arthroscopic examination sometimes revealed a thick remnant ACL with most ruptures occurring in the femoral side or proximal aspect of the substance (Fig. 8) [31]. In these cases, remnant preservation is performed. There are some methods for preparation of the femoral and tibial tunnel. A remnant stump on the femur is minimally debrided (Fig. 9) and a small incision is made at

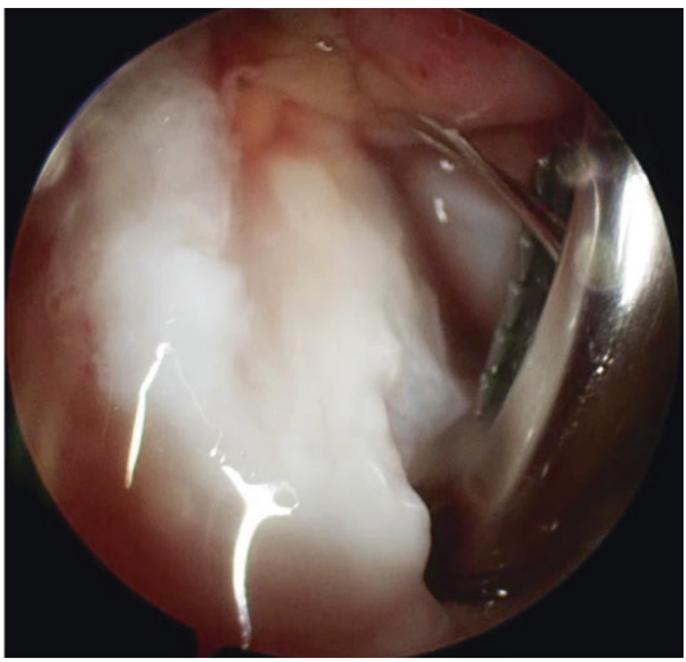

Fig. 6 Arthroscopic image of the guide wire for graft passage. The guide wire inserted from outside to inside through the femoral tunnel is pulled out from inside to outside through the tibial tunnel using a suture grasping forceps

Fig. 7 Sagittal image of magnetic resonance image performed after anterior cruciate ligament reconstruction. An interference screw on tibial side has been inserted out of the tibial tunnel

the tibial stump for locating the guide (Fig. 10). As soon as the reamer penetrated the cortical bone of the tibial plateau, the expansion was created with low speed to prevent further damage to the remnant fibers of the ACL [8, 32]. When too much remnant stump on the femur to expose the femoral footprint, additional far AM portal for traction of the sutured remnant tissue [31], posterolateral (PL) portal using a 70° arthroscope [6], or posterior trans-septal portal using a 30° arthroscope is recommended [29].

Remnant preservation could be divided into two categories. One is that the remnant is preserved as much as possible and the graft is passed into center of the remnant, and then, the remnant is left in situ (Fig. 11) [8, 29, 32, 33]. Another is that the remnant is directly sutured or fixated to the reconstructed graft or another femoral tunnel [6, 31, 34, 35].

Advantages and Disadvantages of Outside-in Technique

Outside-in technique results in a longer mean tunnel length than that of the transportal technique for creating the ACL femoral tunnel [4, 18]. A length of the femoral tunnel is an issue for desiring to avoid the risk of inadequate graft tissue within a tunnel. This is particularly clinically relevant for suspensory fixation using a button and suture loop, because the loop of the device leaves less length of graft within

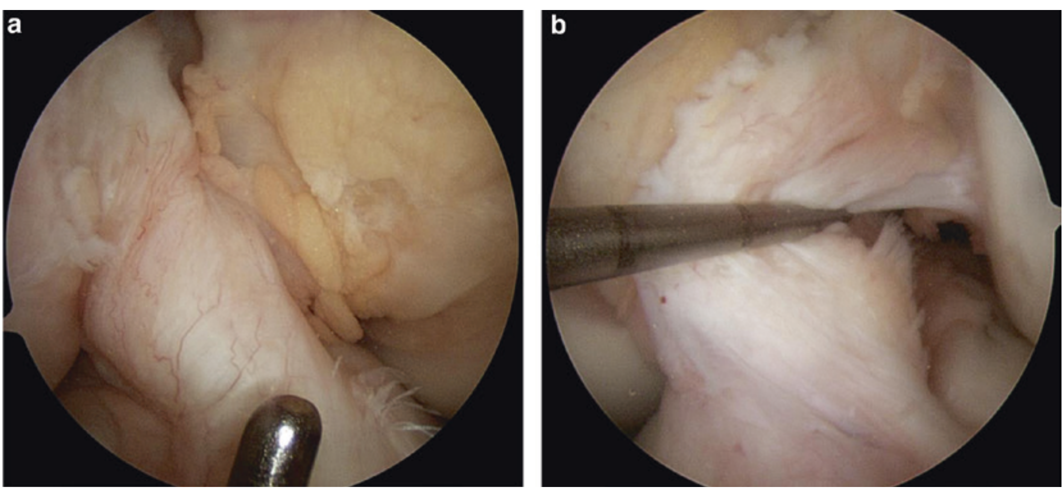

Fig. 8 Arthroscopic images of the remnant of anterior cruciate ligament (ACL). The remnant of ACL adheres to anterior of the original femoral attachment. **a** Right knee. **b** Left knee

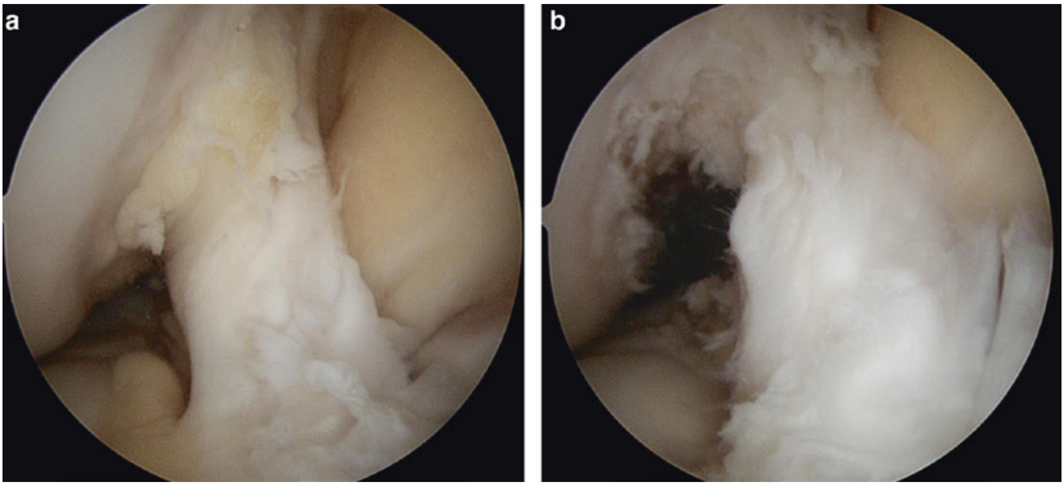

Fig. 9 Arthroscopic images of patient who underwent anterior cruciate ligament reconstruction (ACL) with remnant preservation for right knee. **a** The remnant of ACL is observed. **b** After the remnant stump on the femoral side being debrided minimally

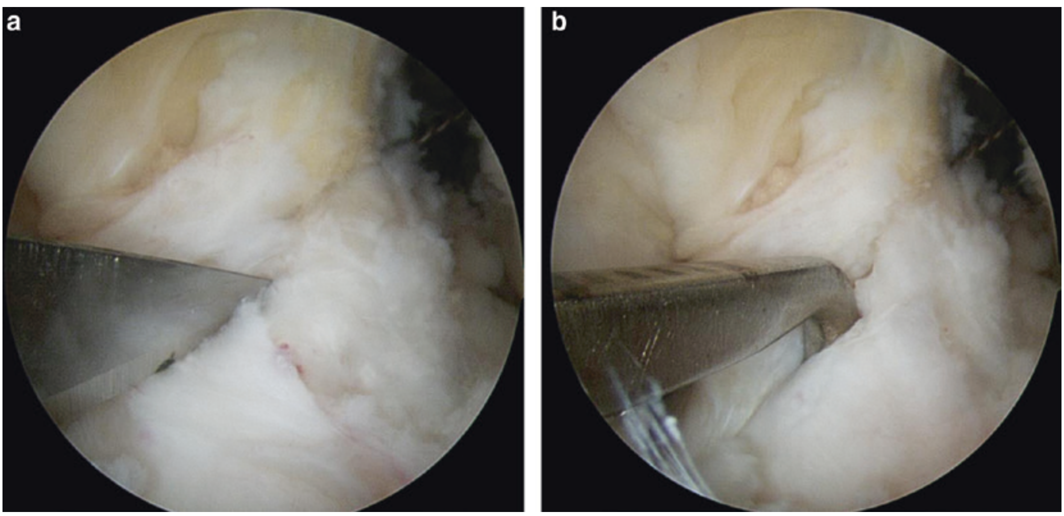

Fig. 10 Arthroscopic images of patient who underwent anterior cruciate ligament reconstruction (ACL) with remnant preservation for left knee. **a** A small incision is made at the remnant stump on tibial side. **b** A tip of the ACL guide is inserted through the anteromedial portal and located at center of the remnant stump on tibial side

the tunnel. However, the minimum length of graft within the tunnel has not been reported in humans [4]. A short femoral tunnel may affect graft healing. In animal studies, long placement of the graft within bone tunnel does not result in an additional increase of graft healing strength [36, 37]. Another advantage of outside-in technique is providing lower risk of posterior wall blowout and iatrogenic medial condyle chondral injury that of complications of transportal technique [38]. Others are predictable near-anatomic placement of femoral tunnel, ease of use for revision ACL reconstruction, and no need for hyperflexion of the knee [5].

Acute bending of the graft and tunnel is a disadvantage of outside-in technique. This may

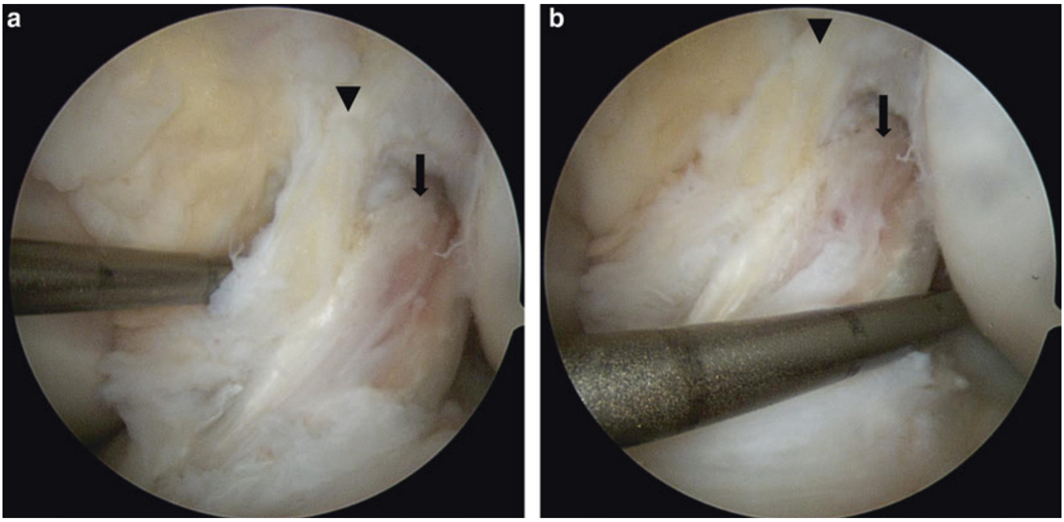

Fig. 11 Final arthroscopic images of patient who underwent anterior cruciate ligament reconstruction (ACL) with remnant preservation for left knee. **a** A probe indicates the remnant of ACL (arrowhead). **b** A probe indicates the reconstructed graft (arrow)

result in complications such as graft immaturity or damage and femoral tunnel expansion [18, 39–41]. Graft bending is defined as the angle between the femoral tunnel and the line connecting the femoral and tibial tunnel apertures [18]. However, these studies have evaluated the graft maturation through signal intensity measured on MRI, therefore, clinical relevance is still unclear. Another disadvantage is surgical morbidity with additional lateral incision [5].

Clinical Outcomes of the Remnant Preservation

Many previous studies have reported the clinical outcomes of remnant preservation compared to non-remnant preservation with ACL reconstruction. Lee et al. [35] performed ACL reconstruction using a hamstring autograft and reported that mechanical stability (Lachmann test, stress radiographs, and anterior stability measured by a KT-2000) did not differ significantly between both groups, however, functional outcome and proprioception in terms of single-legged hop test, reproduction of passive positioning (RPP), and threshold to detection of passive motion (TTDPM) showed significantly better results in remnant preservation than in non-remnant preservation group during a mean 35.1 month follow-up. RPP was tested by measuring discrepancy between the reproduction angle and original angle. Patients were given a flexion device to raise the knee joint at a flexed angle (original angle) with 5 seconds to memorize to angle, and then, patients were instructed to extent the knee joint with 15 seconds. Finally, patients flexed the knee joint at original angle actively (reproduction angle). TTDPM was tested by using continuous passive motion (CPM). CPM was started and was slowly moved into the direction of extension and examiner measured the time when patients recognized the first angle change. Takazawa et al. [33] performed ACL reconstruction using a semitendinosus autograft and reported that negative ratio of pivot-shift test was similar in both groups, however, anterior stability measured by a KT-2000 arthrometer and graft survivorship were significantly better in remnant preserving group than in non-remnant preserving group during the mean follow-up 32 months (range 24–68 months). The limitation of this study was that time from injury to surgery and preinjury

Tegner activity were significantly different between the two groups. However, Naraoka et al. [30] reported that there was no difference in anterior stability measured by a KT-1000 arthrometer and graft maturation measured by a MRI at 2 years between both techniques after index surgery using a semitendinosus autograft. Hong et al. [42] conducted a prospective, randomized controlled trial and reported that anterior stability measured by a KT-1000, negative ratio of pivot shift, passive angle reproduction test, and synovial coverage of the graft evaluated by a second-look arthroscopy did not differ between remnant preservation and non-remnant preservation with ACL reconstruction using a allograft during a mean 25.7 month follow-up. In meta-analyses, the clinical outcomes of remnant preservation with ACL reconstruction in terms of anterior stability were similar to those of non-remnant preservation with ACL reconstruction [43, 44]. Thus, overall, superior clinical outcomes of remnant preservation compared to that of non-remnant preservation have not been demonstrated.

Another issue in ACL reconstruction is bone tunnel enlargement. Although a correlation between tunnel enlargement and poor clinical outcomes has not yet been clearly shown, the presence of large tunnels often severely complicates revision ACL reconstruction and may necessitate staged reconstruction and additional operative procedure [45–47]. Zhang et al. [47] reported that tibial tunnel enlargement measured on plain radiograph occurred within 6 months postoperatively and observed less frequently in remnant preservation than in non-remnant preservation group. At 24 months postoperatively, the percentage of tibial tunnel enlargement was significantly smaller in remnant preservation than in non-remnant preservation group. However, Naraoka et al. [48] reported that remnant preservation did not decrease the degree or incidence of tibial tunnel enlargement measured on computed tomography (CT) at 1 year postoperatively. Masuda et al. [45] reported that remnant preservation reduced enlargement of femoral tunnel but did not affect enlargement of tibial tunnel measured on CT at 1 year postoperatively. Yanagisawa et al. [46] reported that remnant preservation reduced the enlargement of femoral and tibial tunnel measured on CT at 6 months postoperatively.

Conclusion

A rupture of the ACL is common injury and ACL reconstruction has changed over the past decades. One issue in ACL reconstruction is the method of drilling the tunnel into the femur. The outside-in technique may increase the chance of correct graft positioning, reduce the risk of posterior wall breakage and too short femoral tunnel. Recently, satisfactory long-term result of the outside-in technique in ACL reconstruction was reported [2]. In addition, the outside-in technique is relatively easy to preserve the remnant bundle compared to transportal technique.

Theoretically, remnant preservation may allow native tissue to grow into the graft which has a positive effect on graft integration and function. However, the clinical outcomes are still unclear. The most important factor in ACL reconstruction is accurate tunnel in anatomical positions. The position of the femoral tunnel may be affected by the remnant because of poor visual field. Therefore, it is recommended that experienced surgeons are encouraged to perform the remnant preservation with ACL reconstruction.

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The Role of Anterolateral Ligament Reconstruction in Anterior Instability

Jean-Romain Delaloye, Jozef Murar, Charles Pioger, Florent Franck, Thais Dutra Vieira and Bertrand Sonnery-Cottet

Abstract

Since the anatomic description of the anterolateral ligament (ALL) by Claes et al. in [9], there has been a vigorous debate in literature on the existence and the function of this structure first described in 1879 by Dr. Paul Segond. The culmination of this debate was July 2018 and the publication of a consensus paper co-authored by a panel of influential international researchers and clinicians confirming the existence of this ligament. Its origin is posterior and proximal to the lateral epicondyle of the femur and its insertion is on tibia plateau midway between Gerdy's tubercle and the fibular head. Biomechanically, the ALL acts as a rotational stabilizer of the knee and the combined reconstruction of anterior cruciate ligament (ACL) and ALL demonstrated an improvement in knee stability compared with isolated ACL reconstruction. This improvement in knee kinematics has an important clinical impact reducing the rate of ACL graft ruptures and failure of medial meniscus repairs.

J.-R. Delaloye · J. Murar · C. Pioger · F. Franck · T. D. Vieira · B. Sonnery-Cottet (✉)
Centre Orthopedique Santy, FIFA Medical Center of Excellence, Groupe Ramsay Generale de Sante, Lyon, France
e-mail: Sonnerycottet@aol.com

Keywords

Anterolateral ligament · ACL reconstruction · ALL reconstruction · Clinical outcomes · Biomechanics

Introduction

Anterior cruciate ligament (ACL) tears are among the most common knee injuries and the number of ACL reconstructions (ACLR) performed every year is increasing [1]. Isolated single-bundle ACLR is still the gold standard surgical procedure for patients presenting with an ACL tear. However, graft failure rate and persistent rotational instability reflected by a positive pivot shift remains a major concern after the surgery [2]. This residual pivot shift after ACLR showed a negative correlation with functional outcomes and a higher risk of developing osteoarthritis [3, 4]. The influence of different intraarticular surgical procedures or ACL graft choice has been evaluated but didn't show any significant improvement on post-operative outcomes [5–8]. It is for this reason that since the new description of the anterolateral ligament (ALL) by Claes et al. in [9], orthopaedic surgeons have demonstrated a renewed interest in the role of the anterolateral structures of the knee in controlling rotatory laxity and their ability to share

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loads with the ACL graft [9–12]. While some authors demonstrated the ALL anatomy and its important contribution in knee stability others have questioned its role as knee stabilizer and even its existence [13–17]. However, in a consensus meeting in 2017, the ALL was identified as a clear anatomical structure within the anterolateral complex involved in the control of internal rotation of the knee [18]. Additionally biomechanical studies have shown that knee stability was better after combined ACLR+ALLR than after isolated ACLR in the setting of an ALL injury. Finally, this improvement in knee stability could explain the promising clinical results observed in patients who underwent combined ACLR+ALLR [19–22].

History

The ALL was first described in 1879 by Dr. Paul Segond as a "pearly, resistant, fibrous band" that could result in an avulsion fracture of the tibial plateau when the knee was forcefully internally rotated: the Segond Fracture [23]. However, Segond did not describe its precise anatomy and did not name it [24]. In 1914, a french anatomist, Vallois, described the lateral epicondyle meniscal ligament (LEML) whose femoral insertion was on the top of the femoral epicondyle, above the attachment of the lateral collateral ligament and its tibial insertion was on the superior edge of the meniscus [24, 25]. In 1921 in Strasbourg, Jost evaluated Vallois' works in depth and reported that LEML not only had an insertion on lateral meniscus, but also on the tibia. Additionally he mentioned that this ligament was particularly well developed in animals requiring control over rotational stability of their knee [24, 26].

Hughston et al. in 1976 and Prof. W. Müller in 1982 described "a middle third of the lateral capsular ligament" and an "anterolateral femoro-tibial ligament", respectively, providing rotation stabilization of the knee [27, 28].

The term "anterolateral ligament" was first used in literature in 1986 by Terry et al., but its existence was popularized beyond medical journals by Claes et al. in [9] even though many other authors have contributed to the identification of the ALL and the determination of its function [9, 29–34].

Anatomy and Histology

The anatomical characteristics of the ALL have been a source of an intensive debate that ended in 2018 with the publication of the results from the ALC consensus group meeting in London [18]. They confirmed that ALL is a structure within the anterolateral complex (ALC) that included from superficial to deep:

- Superficial iliotibial (IT) band and iliopatellar band
- Deep IT band and Kaplan fiber system
- ALL
- Capsule.

Its origin is posterior and proximal to the lateral epicondyle of the femur [18, 35]. It runs superficially to the lateral collateral ligament (LCL) and then crosses the joint line giving some branching attachment to the lateral meniscus [34, 36–38]. Finally it inserts on the tibia, 413 mm distal to the joint line, halfway between anterior border of the fibular head and the posterior border of Gerdy's Tubercle [9, 18, 36, 37, 39]. According to a reward-winning study published by Claes et al. in [40], this location corresponds to the same location of Segond avulsion fractures [40]. However due to the presence of other structures that also attach on this region, a consensus could not be reached about which of these structures is strictly responsible for this lesion [18].

Following dissection protocols, the ALL could be identified in 83–100% of specimens [9, 36, 37, 39, 41, 42]. According to Daggett et al. a key to successful identification of the ALL is a careful reflection of the ITB from proximal to distal because toward the lateral epicondyle the ITB becomes thin and could closely adhere to the ALL (Fig. 1) [35].

On average, ALL measures 35 to 40 mm in length, 7 mm in width and 1–3 mm in thickness

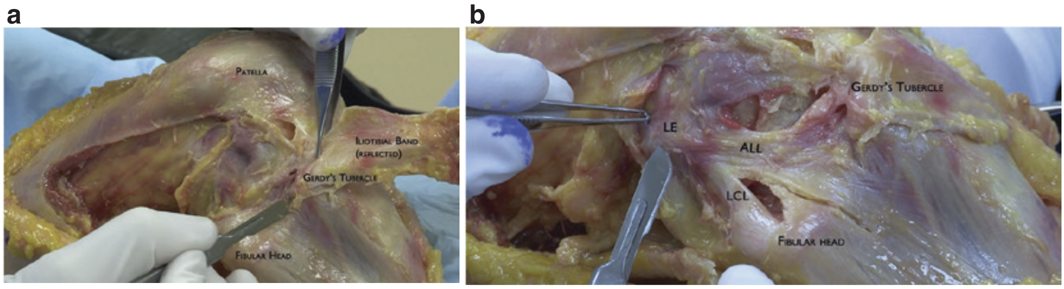

Fig. 1 **a** Careful reflection of the iliotibial band to the Gerdy tubercle is required for visualization of the anterolateral ligament (right knee specimen in supine position). The fibers of the anterolateral ligament are often in close proximity to the deep fibers of the iliotibial band, and meticulous dissection is required to isolate these two structures. **b** After careful dissection, the entirety of the anterolateral ligament (ALL) can be identified as it overlaps the lateral collateral ligament (LCL) (right knee specimen in supine position). The ALL originates near the lateral epicondyle (LE) and inserts onto the tibia between the Gerdy tubercle and the fibular head. *Copyright: Fig. 2+5. Daggett M* et al. *Sugical dissection of the anterolateral ligament. Arthroscopy techniques, vol 5, no1 2016; e185–188*

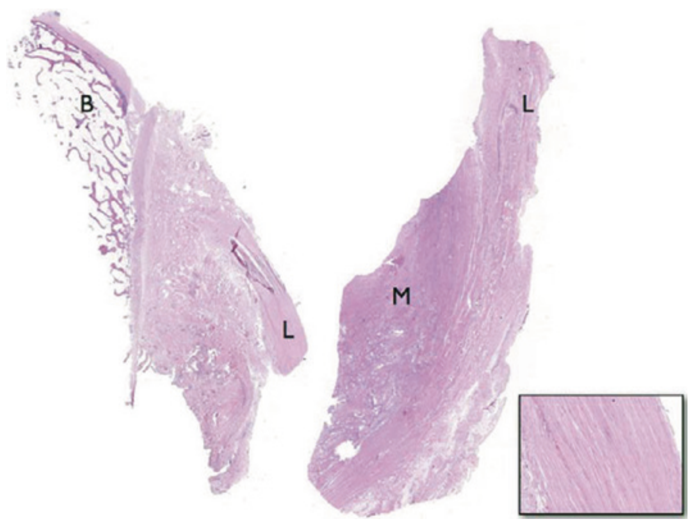

Fig. 2 Sections of the anterolateral ligament (*L*) showing its well-defined femoral bone attachment (*B*) in the left and its meniscal attachment (*M*) in the right. The bottom right image shows the histological structure, with dense connective tissue, arranged fibers, and little cellular material. *Copyright: Fig. 4. Helito C.* et al. *Anatomy and Histology of the knee anterolateral ligament, OJSM 2013*

[15, 17, 42]. Histologically, it is composed of well organized collagenous fibers, fibroblasts, and nerves, indicating a potential proprioceptive role (Fig. 2) [36, 43–45].

Biomechanics and Function

ALL is a stabilizer of the knee whose maximal load to failure and stiffness reported in literature varied from 175 to 205 N and 20 N/mm to 42 N/mm, respectively [39, 46, 47]. These results confirm that a semitendinosus graft (1216 N) or a gracilis graft (838 N) are both appropriate for ALL reconstruction [39].

While results about its contribution in an ACL intact knee remains controversial in literature, it is well documented that the ALL is an important restraint for internal rotation and anterior translation and plays a role in preventing pivot shift in ACL deficient knees [46, 48–50]. Two other structures were reported in literature as actively participating in this knee stabilization: The ITB and the lateral meniscus [46, 51–53]. Indeed Lording et al. and Shybut et al. reported an increased anterior translation and

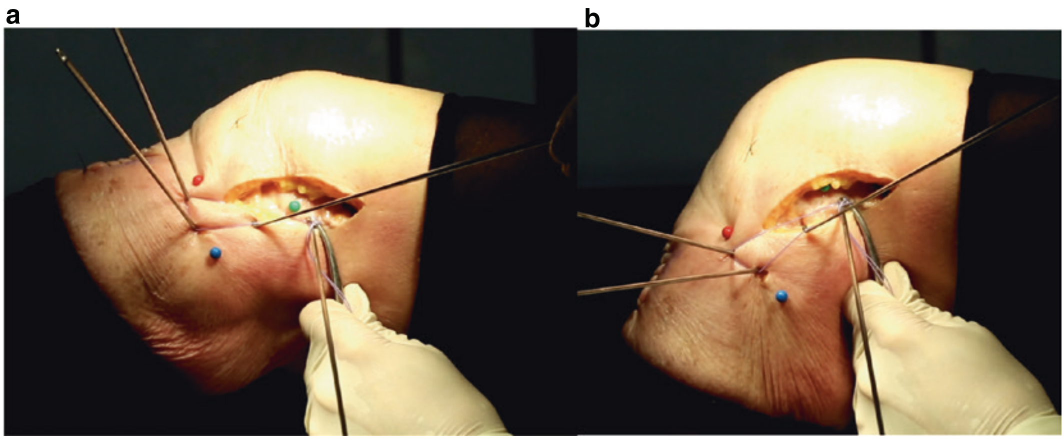

Fig. 3 Simulation of the Anterolateral ligament behavior. In knee extension the suture is tight (**a**) and it is slackened in flexion (**b**). Red point, Gerdy's tubercle; Blue point, fibular head; Green point, lateral epicondyle

internal rotation of the knee after tears of the posterior root of the lateral meniscus [51, 52].

All authors agreed that the ALL is an anisometric structure. However, while some authors reported that the length of the ligament increased with knee flexion, others demonstrated that it decreased [11, 37, 39, 43, 54]. A possible explanation for this disagreement could be related to the previously misidentified origin of the ALL on the femur. With a femoral origin close to or anterior and distal to the lateral epicondyle center, Helito et al. and Zens et al. reported an increase in the ALL length with knee flexion [43, 54]. On the other hand, Dodds et al. demonstrated that the ALL slackened with knee flexion if it originated proximal and posterior to the lateral femoral epicondyle (Fig. 3).

This favorable anisometry would be a condition inherently necessary to allow physiological internal rotation of the tibia during knee flexion and to avoid risk of over-constraint of the lateral compartment of the knee [37, 55].

The problem of length change of the ALL during knee mobilization according to its femoral insertion has been solved by Imbert et al. who demonstrated an identical behavior of the ALL contingent on these two different femoral insertions [56].

Injury

Injuries to the anterolateral structures of the knee can occur at the time of an ACL tear or can be a result of overloading or subsequent giving-way episodes in chronic cases [57]. The traumatic mechanism for a combined ACL and ALL lesion is similar to one for isolated ACL injury: early flexion, dynamic valgus, and internal rotation [13].

Incidence of this injury reported in literature ranged from 80 to 100% of cases [27, 28, 30, 57, 58]. In a recent study, Ferretti et al. systematically explored the lateral compartment in 76 patients who underwent an ACL reconstruction [57]. Macroscopic tears were identified in 90% of patients and were divided as follows (Fig. 4a–d):

- Type I (31.6%): multilevel rupture in which individual layers are torn at different levels with macroscopic hemorrhage involving the area of the ALL and extended to the anterolateral capsule only.
- Type II (26.7%): multilevel rupture in which individual layers are torn at different levels with macroscopic hemorrhage extended from the area of the ALL and capsule to the posterolateral capsule.

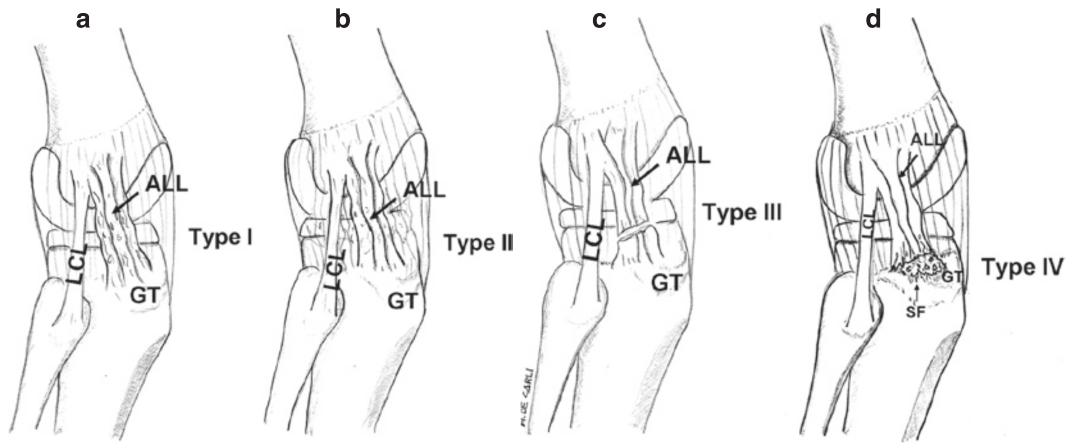

Fig. 4 Classification of injuries of anterolateral complex. **a** Type I lesion: multilevel rupture in which individual layers are torn at different levels with macroscopic hemorrhage involving the area of the ALL and extended to the anterolateral capsule only. **b** Type II lesion: multilevel rupture in which individual layers are torn at different levels with macroscopic hemorrhage extended from the area of the ALL and capsule to the posterolateral capsule. **c** Type III lesion: complete transverse tear involving the area of ALL near its insertion to the lateral tibial plateau, always distal to lateral meniscus. **d** Type IV lesion: bony avulsion. ALL, anterolateral ligament; GT, Gerdy tubercle; LCL, lateral collateral ligament; SF, Segond Fracture. *Copyright: Figs. 2 and 5 Ferretti A* et al. *Prevalence and Classification of Injuries of Anterolateral Complex in Acute Anterior Cruciate Ligament Tears, Arthroscopy 2017, vol 33, 2017:147–154*)

- Type III (21.7%): complete transverse tear involving the area of the ALL near its insertion to the lateral tibial plateau, always distal to the lateral meniscus.
- Type IV (10%): bony avulsion of ALL (Segond fracture).

This study shows that injuries of the anterolateral secondary restraints often occur in cases of apparently isolated ACL tears. This confirms that rotational instability of the knee is not only the result of an ACL tear, but also involves anterolateral structures.

Diagnosis

Clinical diagnosis of an ALL tear remains a challenge for orthopaedic surgeons [13]. The pivot shift test remains the most reliable test to evaluate its integrity. Monaco et al. demonstrated that a grade III pivot shift could be seen only in the absence of both ALL and ACL in vitro [59]. This finding was not confirmed in literature though, as other authors showed that a high-grade pivot shift could be caused by injuries to the lateral meniscus, the iliotibial band, an increased tibial slope, or a general hyperlaxity [13, 60].

With regards to radiology, two modalities are commonly reported on for evaluation of the ALL: ultrasound (US) and magnetic resonance imaging (MRI).

On MRI, although a part of the ALL could be identified in most cases, the entire ligament remains difficult to analyze because of its small thickness and the presence of adjacent structures which cause a partial volume effect in the region [60, 61]. The ligament was entirely visualized in 20.6 to 100% of cases [61–65].

ALL tears also remain difficult to diagnose. In 206 patients with ACL injury, Claes et al. reported that the ALL was abnormal on 162 MRI (78.8%). On the other hand, Helito et al. and Cavaignac et al. identified ALL lesions in 32.6 and 53% of patients with ACL injury, respectively [61, 62]. These rates are far below those reported by Ferretti et al. (90%), which suggests that the false negative rate of MRI in diagnosing ALL injury remains high [57]. However, using a three-dimensional (3D) MRI, Muramatsu et al. identified a higher rate of ALL injury in patients with acute ACL tears (87.5%) as compared to previous authors using standard MRI (Fig. 5) [66].

With regard to ultrasound, Cavaignac et al. demonstrated in a cadaveric study that ALL could be identified with US in all specimens and the findings corresponded precisely to the anatomical dissection [67]. In a comparative study including 30 patients with an acute ACL injury (<3 months old), they also showed that US and MRI could identify ALL tear in 53% and 63% of cases, respectively [62]. Additionally, Segond fracture was identified in 3% of patients on radiographs, 13% of patients on MRI, and 50% of patients on US (Fig. 6).

This higher rate of Segond fracture diagnosed with US is explained by the fact that it has the highest spatial resolution [62]. Time between ACL injury and sonographic evaluation could be an important parameter to consider when analyzing the diagnostic performance. Indeed, Yoshida et al. reported that 33% of ACL-injured knees had abnormalities in the anterolateral structures of the knee when mean time to sonographic evaluation was 4 months (range: 2 days–1 year) [68]. Technically, to identify the ALL on US, the leg has to be flexed and internally rotated placing tension on the ligament. The tibial insertion has to be identified first and then the ALL is followed proximally to its femoral insertion [67].

ALL tears have to be searched for near its tibial insertion. Cavaignac et al. [62] reported that all ALL injuries were at its tibial insertion,

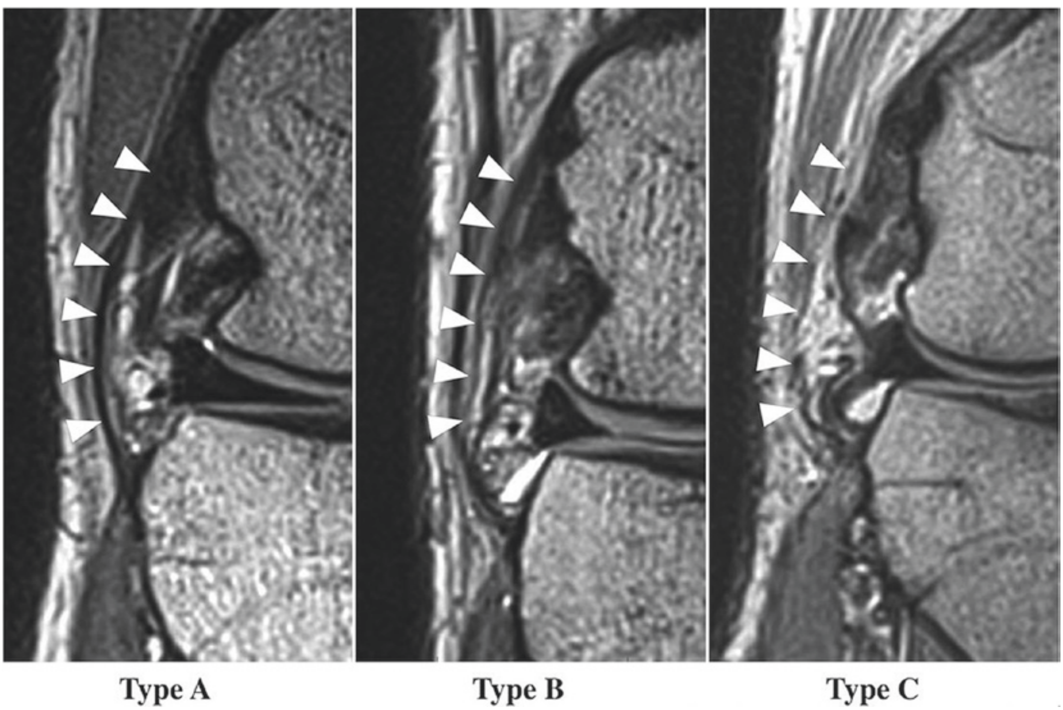

Fig. 5 Injury classification of anterolateral ligament (ALL, arrows) in anterior cruciate ligament deficient knees shown on coronal cross-sectional images: type A, normal ALL, visualized as a continuous, clearly defined low-signal band; type B, abnormal ALL showing warping, thinning, or iso-signal changes; and type C, abnormal ALL showing no clear continuity. *Copyright: Fig. 2 Muramatsu K* et al. *Three-dimensional Magnetic Resonance Imaging of the Anterolateral Ligament of the Knee: An Evaluation of Intact and Anterior Cruciate Ligament Deficient Knees From the Scientific Anterior Cruciate Ligament Network International (SANTI) Study Group. Arthroscopy 2018; 34: 2207–17*

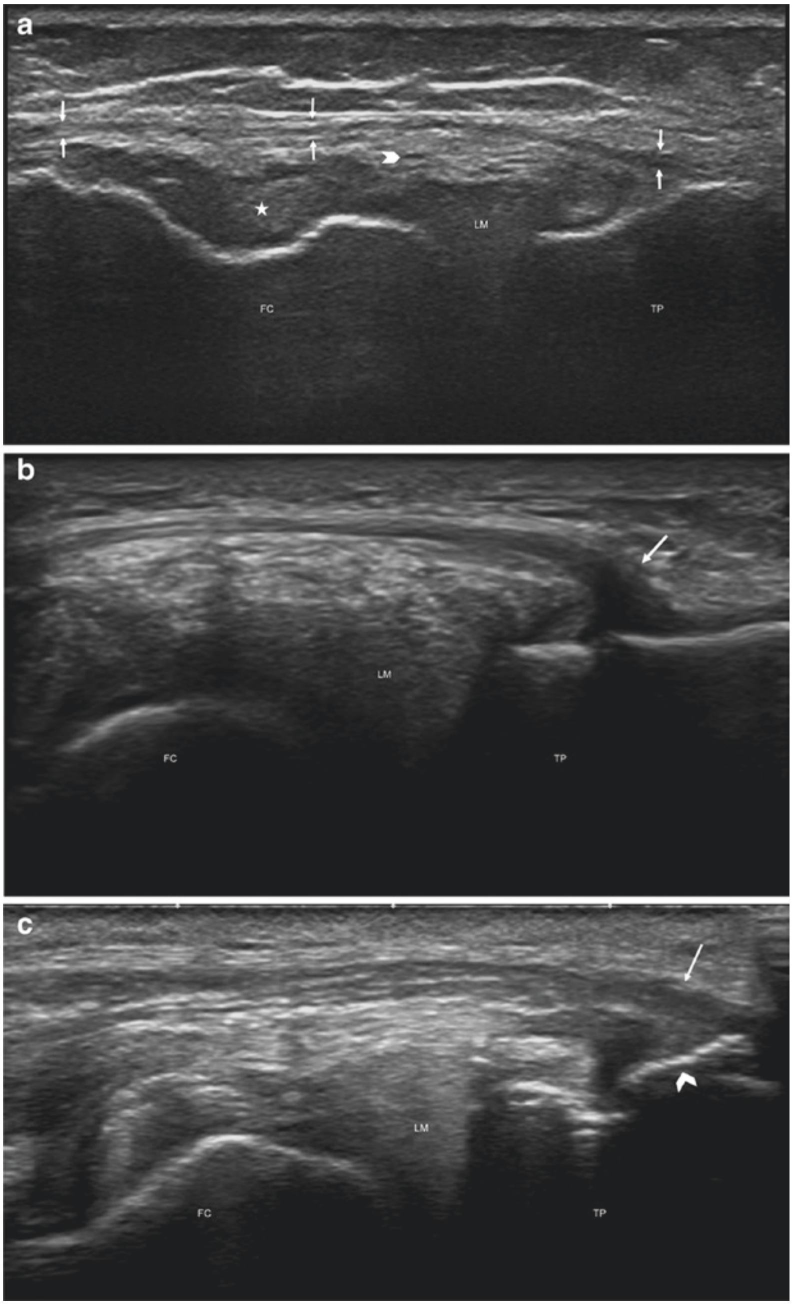

Fig. 6 Appearance of anterolateral ligament (ALL) on ultrasonography. Major axis of the anterolateral ligament of the knee; coronal plane image showing the ligament in the major axis. **a** Ultrasonography of normal ALL (arrows): hypoechogenic, fibrillar, thin structure crossing superficially the inferior genicular artery (arrow-head) and popliteal tendon (star). **b** Ultrasonography of injured ALL: the tibial insertion is hypoechogenic and thickened (arrow) with fluid accumulation in the soft tissues around the ligament. **c** Ultrasonography of injured ALL: the tibial insertion is hypoechogenic and thickened (arrow) and there is a bone avulsion at the tibial enthesis (arrow-head), i.e., Segond fracture. FC femoral condyle, LM lateral meniscus, TP tibial plateau. *Copyright: Fig. 2. Faruch Bilfeld M* et al. *Anterolateral ligament injuries in knees with an anterior cruciate ligament tear: Contribution of ultrasonography and MRI. Eur Radiol 2018;28:58–65*

which was consistent with results of Van Dyck et al. and Claes et al. who found that tibial enthesis was involved in 71.8 and 77.8% of cases, respectively [69, 70]. The predominance of tears in this region could be explained by the biomechanical study of Wang et al. that demonstrated a significantly higher strain in the distal portion of the ALL when internal rotation was applied on the knee [71].

Finally, in a recent systematic review, Puzzitiello et al. have shown that an injury of the ALL, as seen on MRI or US, had a significant correlation with a high-grade pivot shift in most studies [60]. Additionally, although both exams could be useful to diagnose an ALL tear, their actual performance does not allow us to definitively rule out an ALL injury if the imaging findings are negatives.

Surgical Indication

Indications for a combined ACLR + ALLR are questioned in literature due to current lack of clinical evidence [72]. However, based on promising clinical results and evidence that the addition of an extra-articular reconstruction to the ACLR improves rotational laxity, an expert group proposed criteria to identify patients eligible for such surgical procedure (Table 1) [13].

Copyright: Table 3. Delaloye JR et al. *Clinical outcomes after combined anterior cruciate ligament and anterolateral ligament reconstruction. Tech Orthop. 2018 Dec;33(4):225–231.*

Among decisive criteria, members of the international ALC consensus groups agreed that revision ACLR, high-grade pivot shift, hyperlaxity, and young patients returning to pivoting activities represented appropriate indications for an ALLR [18].

Surgical Techniques

Based on anatomical and biomechanical studies different surgical techniques have been proposed for ALL reconstruction using a single or a double gracilis graft [73]. The technique presented below is the one developed by Sonnery-Cottet et al. [74] (Fig. 7).

This minimally invasive ALL reconstruction has demonstrated excellent clinical and biomechanical results [19, 20, 22, 75].

Step 1—Three bony landmarks are marked at the start of the operation (knee 90° of flexion): Lateral epicondyle, fibula head, and Gerdy's tubercle (Fig. 8).

Step 2—One femoral stab incision: slightly proximal and posterior to the epicondyle.

Two tibial stab incisions: 1 cm under the femoro-tibial articulation.

One is just above the superolateral margin of the Gerdy tubercle the other is midway between the previously marked fibular head and the Gerdy tubercle

Table 1 Indication for concomitant ALL reconstruction

Decisive criteria	Secondary criteria
ACL revision	Contralateral ACL rupture
Pivot shift grade 2 or 3	Δ side-to-side laxity < 7 mm
Segond fracture	Deep lateral femoral notch sign
Hyperlaxity	<25 years old
Pivoting sport (High level athletes) Medial Meniscus Repair	
1 decisive criteria or 2 secondary criteria = ACL + ALL reconstruction	
ACL, anterior cruciate ligament; ALL, anterolateral ligament	

Fig. 7 Anterolateral ligament reconstruction. *Copyright:* Fig. 1 A Delaloye JR et al. Clinical Outcomes After Combined Anterior Cruciate Ligament and Anterolateral Ligament Reconstruction Tech orthop 2018

Step 3—Three 2.4 mm K-wires are drilled into the bone through the skin incision at the selected points. A control of the adequate non-isometry can be performed using a suture passed around the guidewires (Fig. 3). The suture has to be tight in extension, and slightly slack in flexion. If it tightens in flexion, then the femoral socket position is too distal and anterior.

Step 4—A 4.5 mm cannulated drill bit is used to overdrill the k-wires and prepare three 20 mm deep sockets. Connect the 2 tibial bony sockets using a right-angled clamp to create a bony bridge. A suture is then passed in a retroverted fashion to create a loop and ease graft passage (Fig. 9B).

Step 5—Harvest the gracilis tendon. Both ends are whipstitched with a number 2 suture.

Step 6—Femoral fixation of the graft. The gracilis graft is passed into an 4.75 mm anchor and then placed into socket (Fig. 9a).

Step 7—Graft passage deep to the iliotibial band using an arthroscopic grasper introduced through the stab incision next to the fibula head. Shuttle of the graft through the anterior

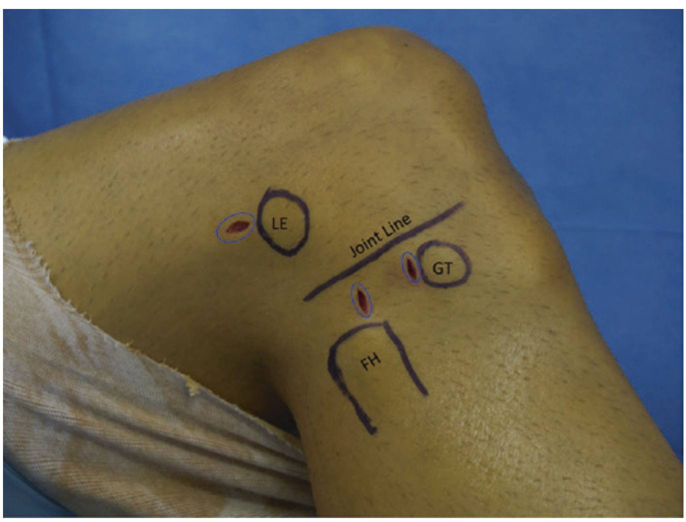

Fig. 8 As shown in a right knee (lateral view), 3 stab incisions (blue ovals) are positioned in relation to the 3 bony landmarks for combined anterior cruciate ligament and anterolateral ligament reconstruction. One is placed on the femoral side, slightly proximal and posterior to the lateral epicondyle (LE). Two tibial stab incisions are subsequently positioned 8 mm below the joint line between the Gerdy tubercle (GT) and fibular head (FH). *Copyright: Fig. 1 Sonnery-Cottet* et al. *Combined Anterior Cruciate Ligament and Anterolateral Ligament Reconstruction Arthroscop Tech vol 5 No 6 2016 e 1253–e1259*

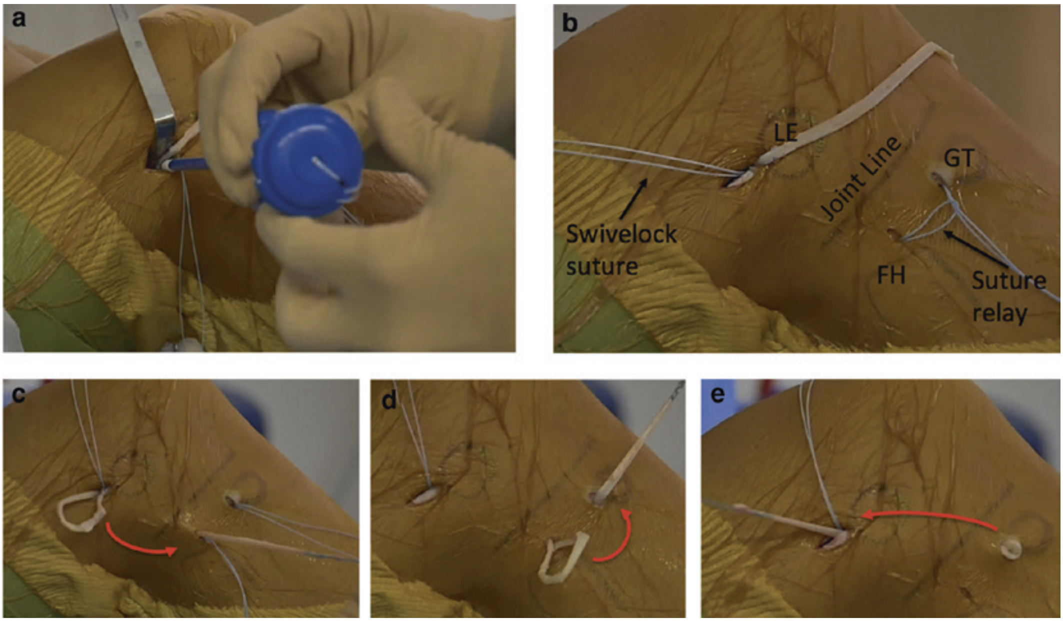

Fig. 9 Right knee. **a** Femoral fixation of one end of the gracilis with the SwiveLock anchor device. **b** a loop of suture relay is placed through the 2 convergent transosseous tunnels. **c** The free end of the gracilis is routed from the femur to the tibia deep to the iliotibial band, **d** through the tibial transosseous tunnel using the suture relay, and **e** back to the femoral incision deep to the iliotibial band. FH, fibular head; GT, Gerdy's tubercle; LE, lateral epicondyle. *Copyright: Fig. 2. Delaloye JR* et al. *Combined Anterior Cruciate Ligament Repair and Anterolateral Ligament Reconstruction, Arthrosc Tech vol 8, No1 (2019); e23-e29*

tibial bone tunnel using the previously passed suture. Introduction of the arthroscopic gasper through the femoral incision and deep to the iliotibial band. Then pull back of the gracilis graft through the femoral incision resulting in a triangle configuration of the graft through the tibial bone tunnel (Fig. 9c–e).

Step 8—Final tensioning of the graft with the knee in full extension and neutral rotation. Fixation of the graft on the femoral side using the sutures outgoing from the anchor.

Post-operative Rehabilitation

After an ALL reconstruction, particularly if performed in conjunction with an ACL reconstruction, the rehabilitation should be carried out in a similar way to conventional ACL rehabilitation [13]:

- Full weight bearing without brace.
- Progressive range of motion exercises. Control of the absence of extension deficit 3 weeks post-operative.
- Gradual return to sports activities is allowed starting at 4 months for non-pivoting sports, at 6 months for pivoting noncontact sports, and at 8–9 months for pivoting contact sports.

Biomechanics of ALL Reconstructions

Several cadaveric studies have examined the kinematics of the knee after ACLR with or without ALLR [75–81].

In the absence of an ALL injury, Noyes et al. and Herbst and al. demonstrated that an isolated ACLR was able to restore the stability of the knee [79, 80]. However, their results also showed that in ALL deficient knee this isolated ACL reconstruction was not sufficient and internal rotation stability of the knee was improved when a lateral extra-articular procedure was added. These results are in accordance with most studies that demonstrated that combined ACLR + ALLR could significantly improve knee kinematics in comparison with isolated ACLR [75–78]. Inderhaugh et al. reported that anatomic ALLR tensioned in full extension, added to ACLR could restore the intact knee laxity in an ACL and ALL injured knee unlike isolated ACLR [75]. This higher knee stability was seen for isolated anterior translation, internal rotation of the knee, as well as stimulated pivot shift. Indeed, except for Noyes et al. who failed to demonstrate an improvement of knee stability when performing a pivot shift test after combined ACLR + ALLR in comparison with isolated ACLR, most other authors demonstrated a higher knee stability during the test when both ligaments were reconstructed [75, 77–80].

A main concern after ALLR is the risk of over-constraint of the knee [76, 78, 80]. Herbst et al. reported a decrease in internal rotation after ACLR and lateral extra-articular tenodesis (LET) in comparison with an intact knee. The largest difference was observed when a combined ACLR and LET were performed in an isolated ACL deficient knee. Interestingly, even in this situation the difference of internal rotation never reached significance. Schon et al. also reported on over-constraint in internal rotation of the knee when ALLR was performed using a semitendinosus graft tensioned at 88 N [76]. This high tension has been highly questioned and may explain the over-constraint observed [82]. Indeed, Inderhaug et al. demonstrated the absence of any over-constraint of the knee when a 20 N tension was applied on the graft [75].

Clinical Results after ALLR

Clinical Outcomes

In 2015, Sonnery-Cottet et al. published the first clinical series of 92 patients who underwent a combined ACLR + ALLR [21]. At a mean follow-up of 32.4 months (range: 24–39 months), Tegner score was 7.1 ± 1.8 and side-to-side laxity was 0.7 ± 0.8 mm. Lysholm, subjective and objective International Knee Documentation Committee (IKDC) scores were significantly improved after surgery ($p < 0.0001$). At final follow-up, 91.6% of patients graded A IKDC subjective score while Lysholm and IKDC subjective scores were 92 ± 9.8 and 86.7 ± 12.3, respectively.

In several comparative studies, clinical outcomes of patients after combined ACLR + ALLR were similar or significantly better than those after isolated ACLR. These observations were obtained regardless of the studied subpopulation (high-risk patient, chronic ACL injury, Hyperlaxity) (Table 2).

Graft Rupture

Although ACL reconstruction is associated with superior quality of life, sports function, and knee symptoms when compared to non-operative treatment, the graft failure rate is up to 18% in high-risk population [83, 84]. Combined ACLR + ALLR have been proposed to reduce the stress applied on the graft during its ligamentization with the expectation that it will reduce the risk of raft rupture [46, 85].

In a comparative study, Sonnery-Cottet et al. demonstrated that combined ACLR + ALLR in a high-risk population was associated with significantly decreased graft rupture rates when compared to isolated ACLR [20]. These graft rupture rates were found to be 10.77% (range, 6.60–17.32%) for quadrupled hamstring tendon (4HT) grafts, 16.77% (9.99–27.40%) for bone-patellar tendon-bone (B-PT-B) grafts, and 4.13% (2.17–7.80%) for hamstring tendon graft combined with ALLR (HT + ALL) at a mean follow-up of 38.4 months (Fig. 10).

In patients with hypermobility and knee hyperextension, Helito et al. also demonstrated a significantly lower graft failure in patients after combined ACLR + ALLR (3.3%) than after isolated ACLR (21.7%) ($p = 0.03$) [86].

In patients with chronic ACL injuries or those with revision ACLR, graft rupture rates at

Table 2 Clinical outcomes and graft rupture rate of comparative studies after isolated ACLR or combined ACLR + ALLR

Author	Date of publication	LOE	Subpopulation	number of patients	Age of patients, mean ± SD or (range),y	Follow-up, mean ± SD or (range), m	Side to side laxity, mean ± SD or (range), mm	Positive pivot shift (%)	IKDC score mean ± SD or (range)	Lysholm score mean ± SD or (range)	Tegner score mean ± SD or (range)	Graft rupture rate, mean, %
Sonnery-Cottet et al. [20]	2017	II	High-risk	22′ ACLR + ALLR	21.8 ± 4.0	35.4 ± 8.4 (24–53)	0.5 ± 0.8	NA	81.8 ± ‘3.’	91.9 ± ‘0.2	7.0 ± 2.0	4.1
				‘76 4HT	23.5 ± 4.0	41.6 ± 7.0 (24–54)	0.6 ± ‘0.0	NA	85.4 ± ‘0.4	91.3 ± 9.9	6.6 ± ‘0.8	10.8
				‘05 B-PT-B	22.1 ± 3.7	39.2 ± 8.8 (24–54)	0.6 ± 0.9	NA	86.8 ± ‘0.5	92.4 ± 8.6	7.4 ± 2.’	16.8
Ibrahim et al. [97]	2017	II	No specificity	56 ACLR + ALLR	26 (20–30)		1.3 ± 0.2	9.4	98.0 ± 5.0 (7°.°-'°°)¹	75.0 ± ‘5.0 (4°.°-8°.°)¹	8.0 ± ‘0.0 (5–9)’	NA
				54 ACLR	26 (2′-32)	27 (25–30)	1.8 ± 0.8	‘2	96.0 ± 3.5 (65.°-'°°)¹	72.0 ± ‘3.5 (4°.°-83.°)¹	8.0 ± ‘0.0 (5–9)’	NA
Sonnery-Cottet et al. [19]	2018	II	No specificity	‘89 ACLR + ALLR	23.8 ± 6.8	36.6 ± 8.2	0.8 ± ‘0.0	NA	NA	93.7 (92.3–95.’)	7.2 (6.9–7.4)	2.’
				‘94 ACLR	30.9 ± 9.9	39.2 ± 9.4	0.9 ± 0.9	NA	NA	93.0 (9′0.3–94.7)	6.5 (6.3–6.9)	5.7
Helito et al. [87]	2018	III	Chronic ACL injury	33 ACLR + ALLR	33.1 ± 8.8	25 (24–28)	1 (1–2)	9.1	92.7 ± 5.9	95.4 ± 5.3	NA	0
				68 ACLR	33.9 ± 6.’	26 (24–29)	2 (1–2)	35.3	87.1 ± 9.0	90.0 ± 7.1	NA	7.4
Helito et al. [86]	e poster	III	Hyperlaxity	30 ACLR + ALLR	27.0 ± 9.1	28.1 ± 4.2	1.5 ± 1.1	26.7	86.9 ± 9.3	88.3 ± 7.3	NA	3.3
	ISAKOS 2019											
				60 ACLR	29.9 ± 8.1	29.6 ± 6.2	2.3 ± 1.4	51.7	84.3 ± 9.8	86.3 ± 7.8	NA	21.7
Lee et al. [88]	2019	III	Revision ACLR	42 ACLR + ALLR	26.8 ± 6.’	38.2 ± 6.9	1.9 ± ‘0.3	9.5	84.3 ± ‘8.5	90.2 ± ‘9.4	7.0 ± 0.8	0
				45 ACLR	27.3 ± 7.6	41.5 ± 8.2	2.2 ± ‘0.4	46.5	75.9 ± ‘9.2	87.5 ± 20.4	6.3 ± 0.7	4.4

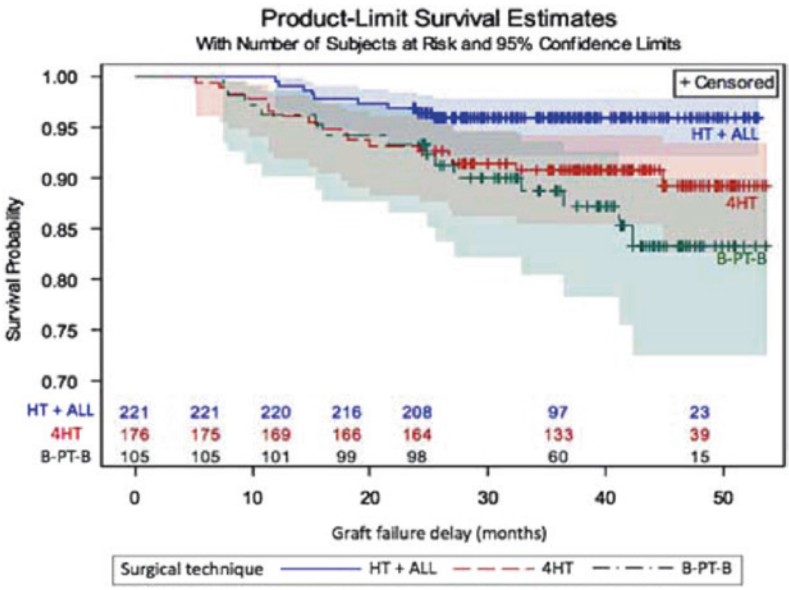

Fig. 10 Survivorship data from Kaplan–Meier analysis stratified by anterior cruciate ligament reconstruction technique. ALL, anterolateral ligament; B-PT-B, bone-patellar tendon-bone; HT, hamstring tendon. Reprinted with permission from American Journal of Sports Medicine. *Copyright: Fig. 3, Sonnery-Cottet* et al. *Anterolateral Ligament Reconstruction Is Associated With Significantly Reduced ACL Graft Rupture Rates at a Minimum Follow-up of 2 Years A Prospective Comparative Study of 502Patients From the SANTI Study Group. Am J Sports Med 2017 45(7):1547–1557*

a minimum 2 year follow-up were also lower in patients with ALLR but this difference was not statistically significant [87, 88].

Finally, In a series of 70 professional athletes with a mean follow-up of 3.9 years, Rosenstiel et al. reported that graft failure after combined ACLR+ALLR was 5.7% [89].

Protective Effect on Medial Meniscal Repairs

Biomechanical studies previously cited have demonstrated that combined ACLR+ALLR improved the rotational stability of the knee in comparison to isolated ACLR [75, 81]. This higher stability could explain the protective effect of the ALLR on medial meniscus repair performed in patients with ACLR [19]. Sonnery-Cottet et al. showed that the survival rate of a meniscal repair at 36-month follow-up was 91.2% (95% IC, 85.4%–94.8) after combined ACLR+ALLR compared to 83.8% (95% CI, 77.1–88.7%) ($p=0.033$) after isolated ACLR. The probability of failure of a medial meniscal repair was more than two times lower if ALLR was performed in patients with ACLR (hazard ratio, 0.443; 95% CI, 0.218–0.866) (Fig. 11).

This protective effect on the medial meniscal repair could play an important role in long-term preservation of the knee articulation in patients after ACLR. Indeed, Claes et al. and Shelbourne et al. reported a three times higher risk to develop OA in patients with meniscectomy compared to those without meniscectomy at a mean post-operative follow-up of 10 years (Odds ratio 3.54, 95% CI 2.56–4.91) and 22.5 years (Odds ratio 2.98, 95% CI 1.91–4.66), respectively [90, 91].

Return to Sport

Low rates of return to sport are a major concern after ACLR, particularly in a high-risk population. One systematic review has demonstrated

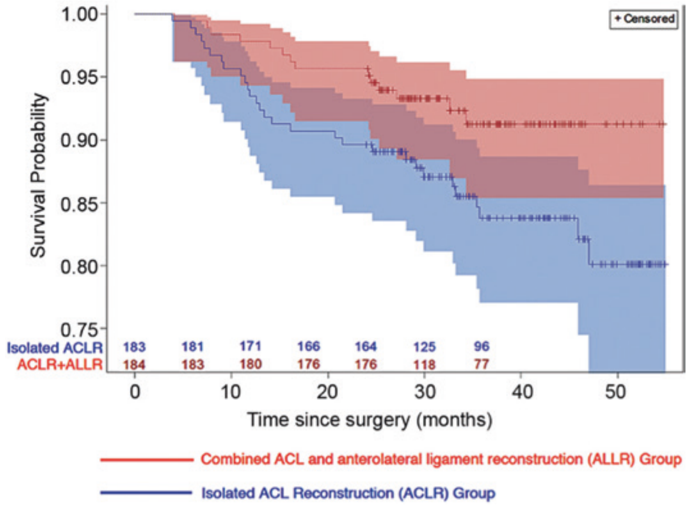

Fig. 11 Kaplan–Meier survivorship with reoperation for medial meniscal injury as an endpoint. ACLR, anterior cruciate ligament anterolateral ligament reconstruction; ALLR, reconstruction. Reprinted with permission from American Journal of Sports Medicine. *Copyright: Fig. 2 Sonnery-Cottet* et al. *Anterolateral Ligament Reconstruction Protects the Repaired Medial Meniscus: A Comparative Study of 383 Anterior Cruciate Ligament Reconstructions From the SANTI Study Group With a Minimum Follow-up of 2 Years. Am J Sports med 2018 Jul;46(8):1819–1826*

that on average, only 65% of patients return to their pre-injury level of sport and only 55% to competitive sport [92].

Sonnery-Cottet et al. reported a higher rate of return to sport for patients who underwent a combined ACLR+ALLR (68.8%) in comparison with those who underwent an isolated ACLR using B-PT-B (63.5%) or 4HT grafts (59.9%). However the difference did not reach statistical significance ($p = 0.231$) [20]. Regardless of the type of graft, factors that significantly increased the return to pre-injury level of sport were male sex and absence of meniscal tear.

After revision ACLR, Lee et al. reported that patients with combined ACLR+ALLR had a significantly higher rate of return to the same level of sports activity than those with isolated ACLR (57.1 vs. 25.6%, $p = 0.008$) [88].

Finally, according to Rosenstiel et al. professional athletes who underwent combined ACLR+ALLR were able to return to the same competitive level of sport in 85.7% of cases with a mean delay from the surgery of 7.9 months (range, 5–12 months) [89].

Post-operative Complications

The rates of reoperation after ACLR reported in literature remain higher than desired varying from 18.9 to 26.7% [93, 94]. Based on historical series of non-anatomic LET that reported high rates of knee stiffness and poor clinical results, concerns existed about the addition of an anatomic ALLR in patients with ACLR [95, 96]. However, more recent studies with a minimum 2-year follow-up demonstrated that this procedure did not appear to be associated with increased risk of reoperation or post-operative stiffness [21, 22, 88, 97]. Indeed, the first clinical series reported that 8 of 92 patients required a reoperation of the ipsilateral knee (8.7%) while 7 patients sustained a contralateral ACL rupture (7.6%) [21]. Thaunat et al. also reported excellent results in a large study of 548 patients, where 77 (14.1%) required an ipsilateral knee reoperation, while 47 suffered a contralateral ACL tear (8.6%) at a mean of 20.4 ± 8.0 months after the index procedure [22]. The only complications specifically related to the ALL procedure (3 patients) were all related to femoral hardware that required removal. Lee et al. also reported one complication in his 42 patients after revision ACLR and ALLR, which was a femoral interference screw protrusion that required removal [88]. Ibrahim et al. reported no patients that needed a reoperation and the only post-operative complication reported in their series of 53 patients with combined ACLR+ALLR was a superficial infection treated with antibiotics [97].

Based on biomechanical results, authors warned of a risk of over-constraint of the knee and early development of arthrosis after ALLR [76, 78]. However, no substantial clinical data is available to confirm or disprove this concern with regards to anatomic reconstruction of the ALL. The only study so far was by Ferretti et al. who showed no increased risk of OA at a minimum of 10 years follow-up in patients who underwent a combined ACLR and LET [98].

Conclusion

The ALL is an important stabilizing structure of the knee whose origin is posterior and proximal to the lateral epicondyle of the femur and its insertion is on the tibia plateau midway between Gerdy's tubercle and the fibular head. In ACL and ALL deficient knees, biomechanical studies have demonstrated that combined ACLR+ALLR restores a higher stability to the knee compared to isolated ACLR. This improvement could explain the excellent clinical outcomes and the reduced rates of graft failure and secondary meniscectomy reported in patients after combined ACLR+ALLR. Furthermore, the addition of an ALLR is a safe and reproducible procedure with no evidence of the adverse events that led to the historical widespread abandonment of other types of LET. As recently reported by Rossi, the question to be considered is not "if" augmentation should be considered, but rather "when" should it be considered, and maybe more importantly, "how" to augment [99]. On going randomized controlled trials (RCT) comparing isolated ACLR and ACLR+ALLR could soon shed light on essential points [100, 101]. Preliminary results of the RCT performing by Sonnery-Cottet et al. will be published later in 2019 [101]. Until then, current clinical data from multiple centers gives confidence in the strength of evidence supporting an important role for ALLR in the ACL-injured knee.

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Revision Anterior Cruciate Ligament Reconstruction

Jae-Young Park and Kyoung Ho Yoon

Abstract

The incidence of revision anterior cruciate ligament (ACL) reconstruction is increasing. For a successful revision ACL reconstruction, the cause of failure must first be identified. Then, the surgeon must make effort to resolve the cause of failure. Tunnel position and widening and bone quality are essential factors the surgeon must keep in mind when performing revision surgery.

Keywords

Revision anterior cruciate ligament reconstruction · Tunnel widening · Tunnel position

J.-Y. Park
Department of Orthopedic Surgery, Uijeongbu Eulji Medical Center, 712 Dongil-ro, Yijeongbu-si,, Gyeonggi-do, Republic of Korea

K. H. Yoon (✉)
Department of Orthopedic Surgery, Kyung Hee University Hospital, 23 Kyungheedae-ro, Dongdaemun-gu, Seoul, Republic of Korea
e-mail: kyoungho@khmc.or.kr

Introduction

Anterior cruciate ligament (ACL) injuries are the most frequent sports injuries and the incidence of revision surgeries is increasing as frequency of ACL reconstruction is increasing [1]. However, the outcomes of revision ACL reconstruction are reported to be inferior to those of primary ACL reconstruction [2].

Cause of Failure

For a successful revision reconstruction of the ACL, the cause of failure of ACL reconstruction should first be identified. The Multicenter ACL Revision Study (MARS) group reported that failure of ACL reconstruction was classified as traumatic, technical, and biological failure, and failure of ACL reconstruction was caused by one or more of these causes [3]. Therefore, for a successful revision ACL reconstruction, efforts should be made to accurately identify the cause of the failure of the primary operation and to resolve it.

Technical Failure

The MARS group reported that the technical problem was the most important cause of failure, when traumatic failure was excluded.

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Especially, malposition of the femoral tunnel was noted as the most common technical problem in a number of studies [3, 4]. The ideal position for femoral tunnel is still debated, however, a femoral tunnel placed too anteriorly results in excessive constraint to the graft in flexion and graft laxity in extension. Posterior wall blowout may be caused by too posterior femoral tunnel positioning, which may result in loss of fixation [4]. Tibial tunnel positioned too anteriorly can cause graft impingement at the intercondylar notch which may lead to consequent rupture of the graft. An excessively posterior tibial tunnel can cause vertical graft [4]. Therefore, it is very important to determine the position of the previous tunnel in order to plan the revision ACL reconstruction. It is helpful to identify the size of the tunnel (degree of bone defect) as well as the tunnel position. Simple radiographs are simple tests that can be used to identify the approximate location and extent of a tunnel and to locate metal implants. Three-dimensional computed tomography (CT) is widely used as the best way to accurately measure the position and size of a tunnel. Magnetic resonance imaging (MRI) is difficult to determine the location and size of the tunnel compared with CT, however, MRI has the advantage of confirming the condition of the graft and detecting accompanying lesions such as meniscal injury.

Biologic Failure

The definition of biologic failure has not been well defined in the past literatures. The MARS group defined biologic failure as lack of incorporation of the graft shown by early failure without any trauma or technical complications with the initial reconstruction [3]. Potential etiologies include failure of biological integration of the graft, failure of bony healing, improper graft tension, or overlooked associated instabilities, such as posterolateral corner injury or medial laxity [5–7]. An increased lateral tibial posterior slope has also been associated with increased risk for early graft failure [8]. The graft tissue used in the initial operation should be identified in case the graft type was the cause of failure. Reusing similar grafts should be avoided in the revision setting. Studies have been reported that the structural properties of allograft tissue may be weakened when exposed to gamma irradiation (4 Mrad), which may cause biologic failure of the graft [9]. The etiology of tunnel widening has not been established and is considered to be multifactorial involving mechanical and biological factors. Biologic factors of tunnel enlargement involve the use of allograft or release of inflammatory cytokines [10].

Traumatic Failure

In the early postoperative period, failure of ACL graft may happen if the graft is traumatized prior to the biological incorporation of the graft [5]. Early return to sports before full restoration of neuromuscular regulation leads to inferior capability of response to stress and more susceptible to repeated trauma [11]. In the late postoperative period, traumatic tear of ACL graft occurs in similar traumatic forces that would result in a primary ACL rupture [11]. As of primary ACL rupture, failures in the late postoperative period typically occur at the mid-substance of the graft.

Examination and Imaging

A thorough review of the patient’s history is important. Review of the initial operation report and arthroscopic findings can give valuable information of the type of graft used, graft fixation devices, simultaneous procedures done, and quality of the articular cartilage and menisci. Also, the patient’s expectations and desired level of activity should be assessed.

A thorough physical examination should be performed. Range of motion of the knee, joint line tenderness, lower extremity muscle strength, and any gait abnormalities are checked. Appropriate exams to ascertain the integrity of ACL, including anterior drawer test, Lachman test, and pivot shift test, are performed. Varus and valgus stress test are performed to test the integrity of posterolateral structures and collateral ligaments. Patients with abnormal hyperextension should be evaluated for posterolateral corner injury.

Imaging should include standing anteroposterior, lateral at 30 degrees flexion, 45-degree flexion posteroanterior (PA) views, and patellofemoral axial views. The 45-degree flexion PA view is needed for the assessment of the joint space narrowing. Anterior, posterior, varus, and valgus stress radiographs are routinely taken to check for concomitant ligamentous injury. Standing full-length views are indicated for evaluation of limb alignment. Tunnel position of the initial surgery and degree of bone loss can be accurately assessed using three-dimensional CT. MRI is taken to provide details of the integrity of the graft. MRI also provides valuable information regarding the condition of articular cartilage, menisci, and surrounding ligaments.

Preoperative Planning

Choice of Graft and Fixation

ACL reconstruction can be performed with a variety of grafts depending on the situation, but autograft shows better clinical results than allograft. According to the MARS cohort, re-rupture was 2.78 times higher when allograft was used [3]. Therefore, if the use of autograft is possible, especially in young and active patients, it is desirable to prepare the graft with the option of autograft in mind. For all revision ACL reconstruction, stronger fixation than initial surgery is recommended. The bone quality and previous tunnel may affect the graft fixation, and single fixation only may not be sufficient enough in these conditions. If there is a difference of less than 2–3 mm between the size of the implanted graft and the size of the tunnel, graft with a large bone plug or an additional screw may be used in addition to the existing fixation screw. If the size difference between the graft and the tunnel is large, two-stage reconstruction is usually performed. Some surgeons consider one-stage reconstruction with the use of grafts with large bone blocks, stacked screws, or matchstick grafting [12].

Tunnel Position and Tunnel Widening

Each tunnel can be divided into (1) well-positioned tunnels (Fig. 1), (2) very malpositioned tunnels (Fig. 2a) and (3) reasonably but not optimally positioned tunnels, depending on location. Generally, if a previous tunnel is formed at the

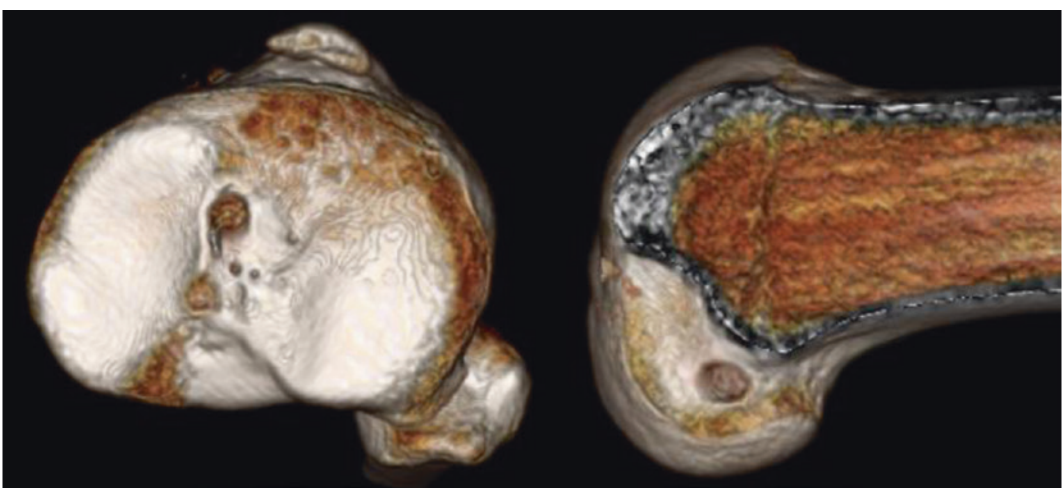

Fig. 1 Three-dimensional computed tomography of the knee showing well-positioned tibia and femoral tunnels

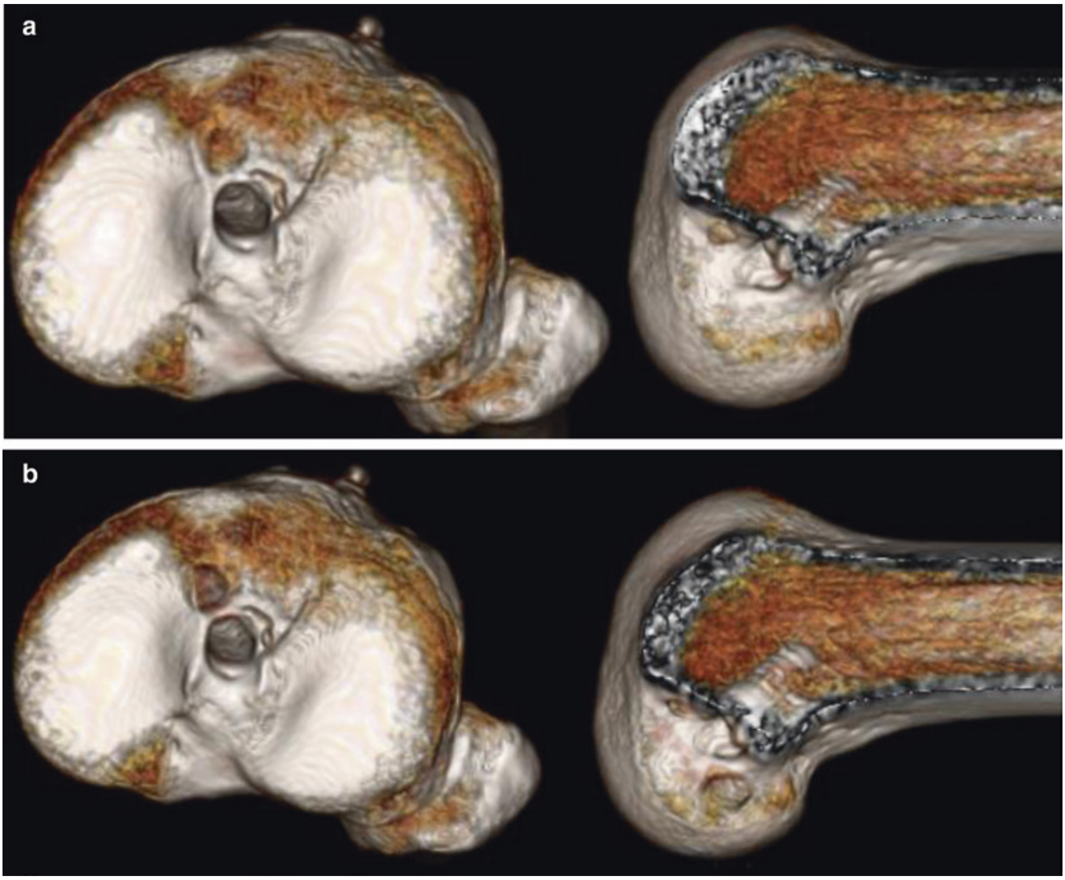

Fig. 2 **a** Three-dimensional computed tomography of the knee showing very malpositioned tibia and femoral tunnels. Tibia tunnel is placed too posteriorly and femoral tunnel is placed too anteriorly. **b** Three-dimensional computed tomography of the knee showing entirely new tunnels created in revision anterior cruciate ligament reconstruction, bypassing the existing tunnels

correct location, the tunnel can be placed at the existing one at the revision procedure. If a previous tunnel is very malpositioned, an entirely new "divergent" tunnel can be created to bypass the existing tunnel (Fig. 2b). The most challenging situation is when the previous tunnel is reasonably but not optimally positioned. Two options are viable. First option is creating a new tunnel. This technique may increase the tunnel size which can be solved by using a large graft with or without a bone plug in combination with bone grafting and larger diameter interference screw. Second option is performing a two-stage procedure. If the graft is expected to encroach into the previously positioned tunnel than the newly drilled tunnel, it is better to proceed with a two-stage procedure after bone grafting first.

Even in well-positioned tunnels, if the bone defect is severe, two-stage reconstruction is considered [13] (Fig. 3a and b). However, there is a disagreement about the degree of bone defect to perform two-stage reconstruction. In general, one-stage operation is possible if the tunnel size is less than 14 mm, and it is better to perform the two-stage operation if the tunnel size is more than 14 mm. However, a recent study reported that the clinical results of single-stage reconstruction were better when the tunnel size was less than 12 mm [14]. It is recommended that the second-stage operation

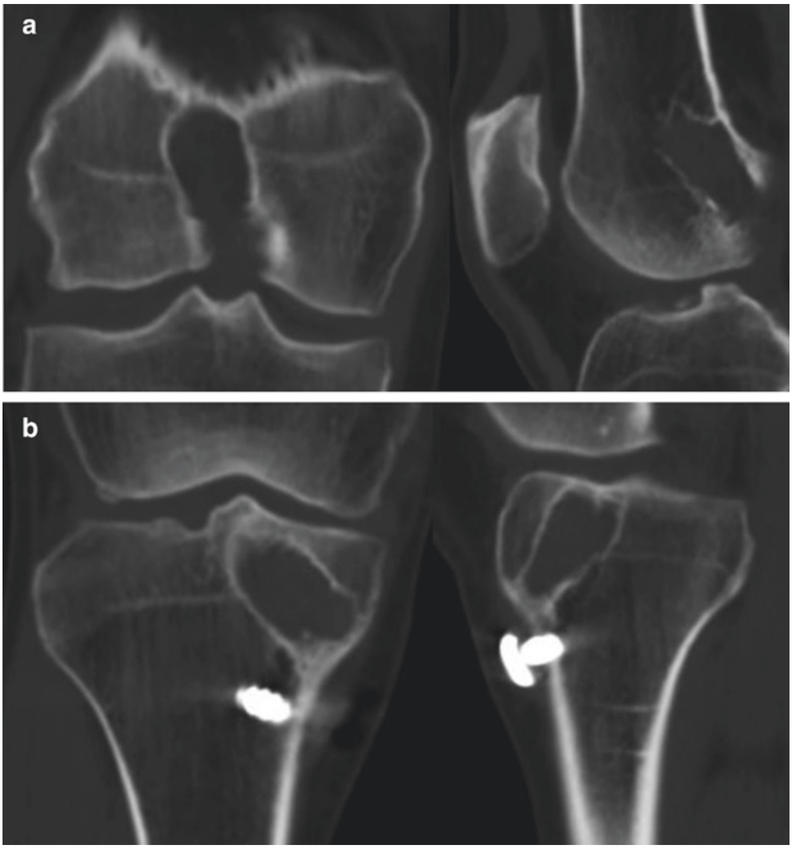

Fig. 3 **a** Computed tomography of the knee showing tunnel widening in the femoral tunnel. **b** Computed tomography of the knee showing tunnel widening in the tibia tunnel

takes place 4–6 months after the first-stage bone grafting operation to properly incorporate the bone graft. Simple radiograph or CT evaluation before second-stage revision ACL reconstruction may aid in evaluation of fusion after bone grafting.

Limb Alignment

Patients undergoing revision ACL reconstruction should be checked for any malalignment. High tibial osteotomy may be considered to address alignment issues accompanying ACL failure [15]. Also, increased posterior tibial slope is considered a predictor for failure of ACL reconstruction and thus should be considered by surgeons [16].

Meniscus Status

The importance of the medial meniscus in the role as a restraint to anterior tibial translation is well documented [17], therefore injury of this part of the meniscus may increase forces on the ACL graft [18]. Tears of the meniscus should be repaired whenever the viability is ensured. Meniscal allograft transplant should be considered in cases where medial meniscus is deficient and severe anterolateral instability is present [19].

Associated Injuries

Associated anterolateral complex injuries, including anterolateral ligament have received interest as an important issue in ACL reconstruction [20]. Combined lateral tenodesis or anterolateral reconstructions with ACL reconstructions have been documented in recent studies [21]. These combined extra-articular procedures may provide supplementary rotational knee stability in the revision ACL revision by decreasing anterior tibial translation and internal rotation [22].

Patient Positioning

Similar to a primary ACL reconstruction, the patient is positioned supine on the operating table. After placement of a pneumatic tourniquet, the operative extremity is placed using a leg holder or against a lateral post upon surgeons' preference. The operative extremity is then prepped and draped in a standard sterile fashion.

Surgical Technique

Standard portals are used for revision ACL reconstruction. Accessory anteromedial portal enables independent drilling of the femoral and tibia tunnels. Outside-in technique enables the surgeon to create divergent femoral tunnel. The senior author uses flexible reamer systems in all revision cases which helps avoid hyperflexion while preparing femoral tunnel.

Diagnostic arthroscopy is first performed. Concomitant meniscal, chondral, and ligamentous pathology should be addressed accordingly.

After the decision is made to continue with revision ACL reconstruction, all existing graft material is removed. Afterwards, assessment of the prior femoral tunnel and associated hardware is done. Removal of the existing hardware is decided on a case-by-case basis. If it is possible to place new tunnels in the ideal position without interfering the previous tunnel or hardware, the tunnels and hardware should be ignored to avoid producing a larger defect in the bone. However, if the existing tunnel or hardware affects placement of the new tunnel positioning, it should be addressed. Same principles apply for the tibial tunnel. After removal of the previous graft material, the remaining tibial tunnel is assessed to determine whether it can be used and whether existing hardware might hinder with placement of the new tunnel. Afterwards, previous tibial incision is used, mostly, for the removal of existing hardware, if necessary. If bioabsorbable interference screw was used in initial surgery, it is sometimes possible to drill the existing tunnel or a new tunnel even if the screw is in contact with the drill.

After preparation of the graft sites, there are three revision options available: (1) re-reaming existing tunnels, (2) drilling new tunnels that avoid existing ones or drilling divergent tunnels, or (3) bone grafting and staged revision reconstruction. The decision needs to be made on a case-by-case basis, taking into account the cause of failure, previous tunnel position and tunnel widening, bone quality of the patient, and concomitant pathologies. If the bone quality of the patient is good, drilling divergent tunnel may be possible when tunnel overlap is encountered. If the bone quality is poor, grafts with large bone blocks, stacked screws, or matchstick grafting may be considered.

A two-stage revision must always be taken into consideration when single-stage revision may cause inferior graft selection, tunnel placement, or fixation of the graft. Primary bone grafting requires removal of all preceding hardware before bone grafting. Allograft is usually used as the source for bone grafting. Autograft is rarely used, however, morselized iliac crest autograft may be utilized. A large allograft may also be designed to fill the defect.

The senior author recommends the use of stronger fixation of the graft for all revision ACL reconstruction. The biological environment of the revision surgery is usually inferior, and single fixation may result in failure of the graft.

Conclusion

Revision ACL reconstruction is technically demanding. A careful analysis of the cause of the failure of the initial surgery is essential.

Surgeon must correct the cause of failure in order to achieve good outcome after revision ACL reconstruction. Basic principles should be followed for a successful revision ACL reconstruction such as adequate tunnel positioning in a good quality bone.

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Rehabilitation and Return to Sports After Anterior Cruciate Ligament Reconstruction

Jin Goo Kim and Dhong Won Lee

Abstract

Return to sports (RTS) after anterior cruciate ligament (ACL) reconstruction is a critical treatment goal for most patients with ACL injuries. In spite of the importance of evaluating knee function in determining its timing of RTS, standardized evidence-based criteria which can be used to determine whether the patients can safely RTS is yet to be developed. As the importance of psychological factors has recently been emphasized whether to return to sports or not, psychological readiness should also be considered in the test battery. Therefore, a simple, reliable, objective, and comprehensive "goal-oriented" test battery is required to assess the possibility of RTS. This chapter aims to analyze the pros and cons of the preexisting functional tests including subjective and objective assessments and describe the future direction they need to develop.

J. G. Kim
Department of Orthopaedic Surgery, Hanyang University Myongji Hospital, Gyeonggi-do, Republic of Korea
e-mail: boram107@daum.net

D. W. Lee (✉)
Department of Orthopaedic Surgery, Konkuk University Medical Center, Konkuk University School of Medicine, Seoul, Republic of Korea
e-mail: osdoctorknee@kuh.ac.kr

Keywords

Anterior cruciate ligament reconstruction · Functional performance test · Functional test · Return to sports

Introduction

Most patients who undergo anterior cruciate ligament reconstruction (ACLR) hope to return to their preinjury sports. However, rates of return to preinjury sport are reported to be often less than be expected, because numerous factors influence whether individuals return to sports (RTS) as well as surgical techniques. Recent review article reported that among 7556 patients, 81%, 65%, and 55% returned to any sport, to their preinjury level of sport, and to competitive level, respectively. [3]. Indeed, some studies showed that the rate of RTS at 6-month follow-up was much lower than previously believed, reporting it to be just 20% [25, 26, 33, 75].

One fundamental question is what constitutes RTS. Recently a consensus statement presented the three elements of RTS continuum [1]. The first is a return to participation, the second is a return to sport, and the third is a return to performance. Return to participation may be participating in rehabilitation, training, or a level

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of sport that is lower than preinjury activity. A return to sport is defined as the patient having returned to their preinjury sport but not performing at the desired performance level. Return to performance presents that the patient is now performing at or above the preinjury level. There has been relatively little empirical data to determine whether patients could return to their preinjury level of performance after ACLR.

Properly designed rehabilitation programs must be developed and implemented to improve the knee function and rate of RTS [32, 48, 68]. Shelbourne KD and Nitz P recommended to speed up the range of motion, to perform an immediate tolerable weight bearing, and to run within 3–4 months after ACLR [73, 74]. Since then, the concept of accelerated rehabilitation with a 30-year history has evolved, becoming incorporated into more scientific sports science in the 1990s. With the advent of the 1990s, sports centers carrying out biomechanics research simultaneously in the United States and Europe, advanced countries in sports medicine, were established. Rehabilitation transcends simple empirical accelerated rehabilitation and establishes a comprehensive active rehabilitation concept that places each element, such as muscle strength, range of motion, functional exercise, which is scientifically designed around the concept of proprioception and neuromuscular control.

Ultimately, assessing knee function after ACLR to determine the timing of RTS is critical, yet a standardized protocol evaluation remains to be developed. There has been a lot of effort to give patients answer how to predict whether a patient will be able to successfully return. Conventionally, time and impairment-based measures such as muscle strength dominated RTS criteria, although deciding RTS is complex and multifactorial. Time was the most commonly used RTS criteria, and it was sole criterion used to clear athletes to RTS in 42% of 209 included studies according to a recent scoping review. In the scoping review, over 80% of 209 included studies allowed RTS before 9 months [13]. It is based on the concept of biology which implies healing of the graft and recovery of neuromuscular function. However, Larsen et al. [47] found that muscle strength and functional capacity of the involved side of recreationally active patients at 9–12 months after ACLR were drastically lower than the corresponding values of the uninvolved side or of healthy matched controls. They suggested that “objective” rather than “time-since-surgery” criteria should be adopted when determining RTS. Hence, measures of impairments and activities are required, although qualitative asymmetries may exist despite quantitative symmetry, and a valid way to measure performance is highly debatable. In this chapter, we will review the postoperative rehabilitation and RTS testing and discuss the future trends of RTS criteria.

Rehabilitation

Range of Motion

Early range of motion (ROM) is appropriate because it can reduce swelling of the joint after surgery, maintain the nourishment of the joint cartilage, and reduce the formation of scar tissue or joint stiffness. After ACLR using hamstring autograft, passive ROM is recommended because active ROM causes musculoskeletal contractions of the muscles using the autograft. The goal of the range of motion for 1 week after surgery should be 0 to 90 degrees, with emphasis on full extension within at least 2 weeks. Full extension is important in the early stages after surgery to restore normal walking patterns quickly. This is because the initial grounding can be stable only when knee extension is completed in normal walking. Then, passive ROM is conducted with the goal of at least 130 degrees until 2–3 weeks. It is also important to make normal movements of the patella to improve ROM, as abnormal movement of the patella is related to the articular fibrosis. For this purpose, a passive patellar mobilization is performed 3 to 4 days after surgery.

Weight Bearing

Compressive loading during weight bearing does not produce further anteroposterior laxity. The weight bearing exercise, such as the central shifting in place early after surgery, is immediately advanced, and normal walking is possible after 2–3 weeks after surgery. This concept is an effort to boldly deviate from the concept of patient carelessly following rehabilitation based on the process of graft in the past, and to encourage neuromuscular control, especially the proprioceptive exercise from the start of the rehabilitation.

Closed Kinetic Chain Exercise and Open Kinetic Chain Exercise

It is known that closed kinetic chain exercise is a relative safe exercise performed by co-contraction of quadriceps and hamstring following ACLR, and that open kinetic chain exercise has a potential of the tibial anterior translation. It is clear that closed kinetic chain exercise is a good method after ACLR because it is in a similar form to functional performance and is not burdened by shear force generation. However, there have recently been reports of similar degree of tibial translation during open kinetic chain exercise compared to closed kinetic chain exercise. During open kinetic chain exercise such as leg extension machine, the anterior and posterior translation of the tibia is occurred. In the case of 45-0 degrees, which is called the neutral angle, the anterior translation of the tibia occurs and in the case of 90–45 degrees, the posterior translation occurs, so early application of the open spindle movement is possible. Closed kinetic chain exercise, such as squats, can be conducted gradually from 1 to 2 weeks. In open kinetic chain exercise, 90–45 degrees extension, which the anterior translation of the tibia is not generated, is performed after 6 weeks. After 12 weeks, all range of motion can be carried.

Hamstring Exercise

ACLR using hamstring autograft usually results in flexor weakness of 10–30%, and it is recommended to start isolated leg curl exercise at 6 weeks after the surgery. However, depending on the degree of pain, voluntary flexion exercise can be started from 3 weeks against gravity, and the weight is added progressively at 6 weeks. Eccentric contraction is performed at 5 months after the surgery.

Functional Brace

In theory, using a functional brace after ACLR is biomechanically and functionally helpful, but there is a lack of evidence to prove [62]. We suggest that development of a functional brace that can support a natural function reproducing the action of ACL, while also playing a positive effect on neuromuscular control, even in dynamic physical activities.

Step-by-Step Program

Step 1 (0 to 3 Weeks)

The goal of this step is to control inflammation and edema, to activate quadriceps muscle with full extension, and to educate the general content of rehabilitation. ROM exercise is started progressively within the control of the pain, and the goal is to achieve 90 degrees for 1 week after the surgery, and to achieve at least 130 degrees by 3 weeks. For this purpose, the patients use CPM equipment and a fixed bicycle within 2 weeks. It is important to increase activation of quadriceps muscle, and to achieve this, it is necessary to restore neuromuscular control capability of the weakened knee joint by performing a quadriceps set-up early.

Regarding weight bearing, immediate tolerable weight bearing is encouraged as soon as possible, and weight shifting exercise is started at 2–3 days after ACLR. Then, normal walking is allowed at 2–3 weeks after the surgery. In addition, standing and lifting of the heel as a calf muscle exercise is performed.

Straight leg raising (SLR) is carried out when full extension is possible. Squats leaning against the wall are carried out at 2 weeks after the surgery.

Step 2 (4 to 6 Weeks)

The goal of this step is to proceed normal walking and proprioception training and to begin muscle strength exercise.

Normal walking training with full extension is conducted using treadmills. For proprioception training, patients are trained to stand on single leg and balance themselves. This training begins with a single leg on a stable ground and is conducted on an unstable ground. It also allows more advanced squats to improve lower extremity muscle strength and can further practice walking up and down stairs using the step-box.

At this stage, active leg curl exercise without weight is started.

Step 3 (7 to 12 Weeks)

The goal of this stage is to emphasize the high level of strength exercise to restore both proprioception and muscle strength.

If the patients performed well in the previous step, they can perform more advanced proprioception training, such as writing Alphabet or numbers with single leg with their eyes closed. Additional force equipment, such as leg press machines, can be carried out at a limited angle. Leg extension machine with weight added at the range of 90–45 degrees, which does not cause the anterior translation of the tibia until 12 weeks is conducted. Also, from this stage, the leg curl machine is performed through the weight resistance.

Step 4 (13 to 18 Weeks)

The goal of this step is to begin functional training to prepare RTS with improved muscle strength and muscle endurance. At the end of 3 months following ACLR, muscle strength testing, balance testing, anterior laxity test such as KT-2000, and subjective questionnaire are conducted. To pass the tests, the involved side reaches 70% or more compared to uninvolved side on each item.

When the hamstring autograft is used for ACLR, a 3-month period or so results in some degree of tendon regeneration, which is a step to boldly remove the initial protection and start a light running [49]. From this stage, we need to slowly raise the number of unstable factors that could result in graft re-rupture within patients' manageable rehabilitation programs, based on the theory of various mechanisms of feedback and feedforward. Through repeated training the patient can overcome the unexpected instability that could result from returning to the actual sports activity. To overcome fear of re-injury should be emphasized. Therefore, this step is very important to RTS and avoid re-injury, so actions to perform feedforward mechanisms should be presented in the rehabilitation program from low to high levels.

Along with light running, two-legs jumping can be added, and as the process progresses, single leg or gradually reversed and running or jumping are performed. Plyometric exercise which induces immediate concentric contraction after eccentric contraction is also conducted. In addition, the perturbation training is carried out by adding a method of training that stimulates the patients to shake the center in an unexpected situation.

Step 5 (19 to 24 Weeks)

The goal of this step is to perform training for RTS such as speed, agility, and specific functional exercise. The full preparation for RTS is made by switching from previous simple direction to a more diverse direction with movements of running or jumping in a more power-driven manner.

It is recommended that the patient can return to sports when the involved side reaches at a level of 85 to 90% of the uninvolved side in each item by performing muscle strength test, functional performance test, balance test, anterior laxity test using KT-2000, and subjective questionnaire at 6–9 months after ACLR.

RTS Criteria

Patient Reported Outcome Measures

Subject knee scores may be useful when deliberating patient safety of RTS. Recent scoping review reported that patient-report criteria were used in 12% of the 209 studies [13]. Recent assessments used in research in the field of sports medicine include 36-item Short-Form (SF-36), Lysholm Score, Knee injury and Osteohrritis Outcome Score (KOOS), International Knee Documentation Committee (IKDC) sub-subjective score, Tegner activity scale, and Cincinnati knee rating system. Among them, Lysholm score, IKDC [14, 22, 30, 40, 51, 52, 75]. Lysholm score and IKDC subjective score are recorded based on subjective judgment of each patient on daily activities. The questions of IKDC subjective score include not only the function of the knee joint, but also the role of the knee joint in daily activities and psychological contexts, it is deemed more useful compared to them of Lysholm score. Further, the advantage of IKDC subjective score is that the scoring system does not change according to the sex or age of the patients, and it can represent various knee-related complications [55, 63, 66]. The Tegner activity scale is a subjective indicator of a patient's level of sports activity and is often used as the basis for determining appropriateness of RTS compared to the preinjury level of sports activities [14, 58, 75]. Sousa et al. [75] found that the patients who successfully returned to sports at 6-month follow-up showed over 85% of uninvolved side in isokinetic strength test and over 90% of uninvolved side in each functional test (vertical jump, single hop, and triple jump tests), and they had significantly higher IKDC subjective score and Tegner activity scale compared to patients who failed to return to sports. Kong et al. [40] reported that IKDC subjective score and Tegner activity scale were significantly correlated with functional performance tests (Co contact, Carioca, and Shuttle run tests) at 6 months after ACLR.

Instability Tests

After ACLR, the anterior and rotational stabilities can be evaluated through the Lachman test, the anterior drawer test, and the pivot shift test. These tests are part of impairment measures. Makhmalbaf et al. [56] reported that conducting these tests under general anesthesia can improve the accuracy of measurements and that the sensitivities of the Lachman and the anterior drawer tests were 93.5% and 94.4%, respectively. A better approach to objectively measure anterior instability is using arthrometers, such as the KT-1000 arthrometer (MEDmetric, San Diego, CA, USA), the Genucom Knee Analysis System (FARO Technologies Inc., Lake Mary, FL, USA), and the Rolimeter (Aircast Europe, Neubeuern, Germany). Pugh et al. [65] showed that KT-1000 arthrometer and Rolimeter show superior validity over stress radiography derived from the TELOS^{TM} (Laubscher & Co., Holstein, Switzerland). Some studies defined a criterion of <3 mm side-to-side difference for clearance to RTS [13].

A restored rotational stability, which is commonly measured using the pivot shift test, is one of the important determinants of whether a patient can safely return to sports [7, 42, 43, 54]. The pivot shift test significantly correlates with the outcomes of subjective assessments and of functional scores and with RTS [39]. However, parameters contributing to the pivot shift phenomenon include tibial internal rotation, anterior translation of the lateral tibia, and sudden acceleration of the posterior tibia, and these distinct phases of dynamic rotatory laxity are difficult to differentiate manually. There is need to expand the grading system to include more clinically relevant sub-classifications and to develop quantitative approaches to measuring pivot shift. To this end, numerous studies have investigated ways to quantitatively measure pivot shift and to improve the accuracy of these quantitative value. Measurement devices of pivot shift tests have been developed such as navigation systems, [27, 59] electromagnetic sensors, [41] inertial sensors, [45, 87] and image analysis systems [6, 76]. Low-cost, non-invasive, and self-contained devices are gaining popularity for their ease of use. Like inertial sensors, image analysis systems are relatively cost-effective and non-invasive. However, limitations include that image analysis systems are not able to measure the actual movement of bone, possibly leading to errors in assessment, and that the sensitivity of this measurement method can be compromised when the marker escapes the measurement field, the camera is misplaced, or the axial movement test is conducted more quickly than the frame rate of the camera. Future work is required to improve their reliability and validity to a level comparable to those of high-cost systems such as navigation systems and electromagnetic sensors. Furthermore, new mechanical applications of the devices which are able to detect real three-dimensional movement and to standardize the force applied during the pivot shift test are needed.

As limitations, these instability tests are performed with the knee muscles in relaxation and in an open kinetic chain system. They are not able to reflect the functional and dynamic performances that occur in a closed kinetic chain system in sports activities [23, 25, 26, 28, 29, 53, 60]. In a closed kinematic environment, the role of muscles in contributing dynamically to stability of the knee joint are complex and hard to evaluate.

Muscle Strength

Muscle strength tests are also part of impairment measures. Recent review article reported that 41% of 209 studies included muscle strength as RTS criterion [13]. Because muscle strength is vital for functional performance of the knee, restoration of muscle strength, specifically the isokinetic strength, is an important factor for deciding whether a patient can safely return to sports [7, 21, 22, 29, 35, 36, 38, 52, 69, 79]. Risberg and Holm [69] found that the peak extensor torque and the peak flexor torque were 88.5% and 92%, respectively, of the contralateral healthy side at 2 years after ACLR. Kim et al. [36] reported that the peak extensor torque of hamstring autograft group and allograft group at 2-year follow-up were 83% and 81%, respectively, of the involved side. The corresponding values for peak flexor torque of both groups were 87% and 95%, respectively. They showed that standard flexion deficit was significantly correlated with Carioca test, Co-contraction test, Shuttle run test, and single leg hop for distance (SLHD) test, whereas deep flexion deficit was not correlated with functional performance tests. According to a recent systematic review, muscle weakness after ACLR is highly influenced by the graft donor site. Moreover they revealed that harvesting of hamstring autograft was followed by prominent flexor weakness while harvesting of the bone-patellar tendon-bone (BPTB) was followed by prominent extensor weakness [86].

Most studies demonstrated that quadriceps muscle strength is correlated with good clinical outcomes after ACLR. Keays et al. [35] reported that quadriceps muscle strength, but not hamstring muscle strength, was significantly correlated with the functional tests (Shuttle run, Side step, Carioca, and Single and Triple hop tests) at 6 months after ACRL using hamstring autograft. These results suggest that "quadriceps-avoidance gait" occurs in the patients who have ACL injury, and it leads to markedly weakened extensor peak torque. Otherwise, hamstring acts as a compensatory mechanism. Because the hamstrings role as an important agonist to the ACL pulling the tibia backwards. Hence, quadriceps strength exercise plays an important role in recovering the knee function [35, 37, 69, 72].

The most commonly used evaluation tool for muscle strength was isokinetic strength at 60 °/s, which means movement at a constant speed according to recent systematic review [61] (Fig. 1). Numerous studies found that the isokinetic strength tests have a significant correlation with running, cutting, and single leg hop tests, whilst others reported that they are correlated with only single leg hop tests [8, 31, 34]. Although the efficacy of isokinetic strength tests on functional performance is unclear, general consensus is that isokinetic extensor strength demonstrating a LSI (limb symmetry index)

Fig. 1 Isokinetic strength test using dynamometer

lower than 10–15% is appropriate for RTS [13, 61, 79].

Since activities such as landing after jump, and pivoting in soccer, handball, or basketball require a lot of eccentric contraction, the feasibility of using only assessment of isokinetic strength to determine RTS in questionable [10]. It is a task to develop to measure endurance of the quadriceps and hamstring muscles as the fatigue of them can decrease dynamic knee stability and result in re-injury [77, 78, 85].

Functional Performance Assessments

During sports activities our lower extremities undergo repeated deceleration and acceleration, which requires an extensive and convoluted control from the neuromuscular system. Therefore, simple quantitative evaluation of muscular function that does not take into account neuromuscular control cannot be an accurate flection of muscular function [84]. Hence, preexisting evaluation methods to determine RTS have limitations in determining real function, so efforts have been made to find more suitable methods of assessing the functional performance.

Assessing single leg performance is useful because unilateral deficits masked by bilateral leg movements in sports can be detected. Conventionally, single leg hop tests have been used as test to decide RTS, and recent review found that at least one hop test as a RTS criterian was used in 14% of 209 included studies [13]. For muscle strength tests and hop tests, limb symmetry index (LSI) is commonly used to calculate the difference in score between the uninvolved limb and involved limb. The threshold LSI for RTS has been shown to be 80% to 90%. Previously, 93% and 100% of healthy individuals have shown on the preexisting single hop tests to demonstrate a LSI of greater than 85% and 80%, respectively [9, 22, 60, 70]. On the basis of these findings, we require a LSI of 85% or greater to determine the patient's preparedness for RTS.

There are various types of hop tests. The single leg hop for distance test is used widely as a functional performance test after ACLR because it shows a high degree of reliability [7, 19, 20, 22, 67] (Fig. 2). Barber et al. [8] revealed that their test battery consisting of the single leg hop for distance test and the single leg vertical jump test (Fig. 3) provided a more reliable indicator of knee function after ACLR than the isokinetic strength test. Moreover, using the single leg hop for distance test in combination with two or more hop tests can increase its sensitivity [8, 60, 67]. The test battery developed by Gustavsson et al. [23], which consists of the vertical jump,

Fig. 2 Single leg hop for distance test. The subject is asked to hop forward as far as possible, jumping and landing with the same foot. The longest distances for the affected and unaffected limb are measured in centimeters using a ruler

Fig. 3 Single leg hop for jump test. The subject is asked to perform a single deep squat with pause, followed by vertical jumping for maximum height with one leg on a contact mat of a jump analyzer which measures jump height (cm)

the single leg hop for distance, and the side hop, showed a sensitivity of 87% and an accuracy of 84% and demonstrated a high ability to discriminate between hop performance of the involved and the uninvolved side. Assessing the 30-second sideward endurance in patients, they suggested that side hop induced muscle fatigue necessitates a strong control of dynamic stability, which may be why the test battery is effective in discriminating hop performance between the involved and uninvolved side. Recently, several devices have been developed to measure the score of hop tests, such as the computerized contact mats, which can be used to measure height even in restricted spaces at one time-point [50].

The functional performance tests proposed by Lephart et al. [53] are (1) Co-contraction test which reproduces the rotational forces that generate tibial translation; (2) Cariocoa test which reproduces the pivot shift phenomenon; and (3) Shuttle run test which reproduces the acceleration and deceleration forces (Fig. 4). Ko et al. [38] reported that these three functional performance tests had a high level of test-retest reliability when conducted in healthy people and showed a significant correlation with Tegner activity scale. It is suggested that these tests can reflect the daily activities. Especially, Co-contraction and Carioca tests are reported to be useful in assessing rotational instability in dynamic situation which is an important factor in assessing RTS after ACLR [29].

The 2016 consensus on RTS outlines 5 recommendations to guide the choice of tests, and the first is use of a group of tests (test battery) [1]. Although, assessing movement quality or other performance-based tests require more complex equipment, large amounts of space, and are more difficult to standardize. However, if we only test for impairments, there would be lack of information about the patients' capacity to cope with all of the physical demands during sports activity. Herbst et al. [25] and Hildebrandt et al. [26] reported seven functional tests (the two-leg stability test; one-leg stability test; two-leg countermovement jump; one-leg countermovement jump; plyometric jumps; speedy test; and quick feet test) with high level of test-retest reliabilities. Using these tests, they showed that the proportion of patients returning to "non-competitive sports" after ACLR was 15.9% at the 5.7-month follow-up and 17.4% at the 8-month follow-up, and among the patients only one was eligible to return to "competitive sports". They conclude that the majority of patients at the 8-month follow-up failed to pass each of the seven functional tests for RTS. They emphasized that the minimum 6-month threshold to return to sports should be revised, and strongly advised against premature return to competitive sports. Returning to sports before graft maturation, which may take up to 12 months, would put the individual at risk of both re-rupture and contralateral ACL rupture.

Recently, a movement quality test such as Landing Error Scoring System (LESS) is used as part of a test battery [82]. Many authors reported that LESS may be a significant predictor for patients passing all RTS criteria after ACLR, because asymmetrical movement patterns such as increased knee valgus are suggested to increase re-injury [18, 80, 83]. Therefore, it is recommended to add movement analysis in the test battery. Another test for assessing balance and dynamic control is the Y-Balance test (YBT), which was derived from the star excursion balance test and is a relatively simple and reproducible test [7, 57] (Fig. 5). Reduced performance and a high LSI as determined through the YBT have been shown to be associated with increased risk of lower extremities [64].

Improvements in test battery through advanced digital sensor and internet technology may lead to easier and real-time measurements of knee performance.

Psychological Assessments (Fear of Re-Injury and Confidence)

Regarding RTS, patients' psychological factors should not be overlooked, hence, increased interest in psychosocial factors in patients has led to vast volumes of research within the recent 20 years. It was reported that more than 50% of patients who could not return to sports showed fear of re-injury [17, 52]. Fear of re-injury is one of the deterrents of RTS in patients without prominent lack of knee function in functional tests and that lowered confidence in performing sports activities affected both short- and long-term outcomes, including the rate of RTS [5, 44, 71].

Using the Tampa Scale of Kinesio (TSK) for phobia, Kvist et al. [44] conducted a study in which they measured fear of re-injury from sports. They found that 57% of patients did not achieve preinjury level of sports activity

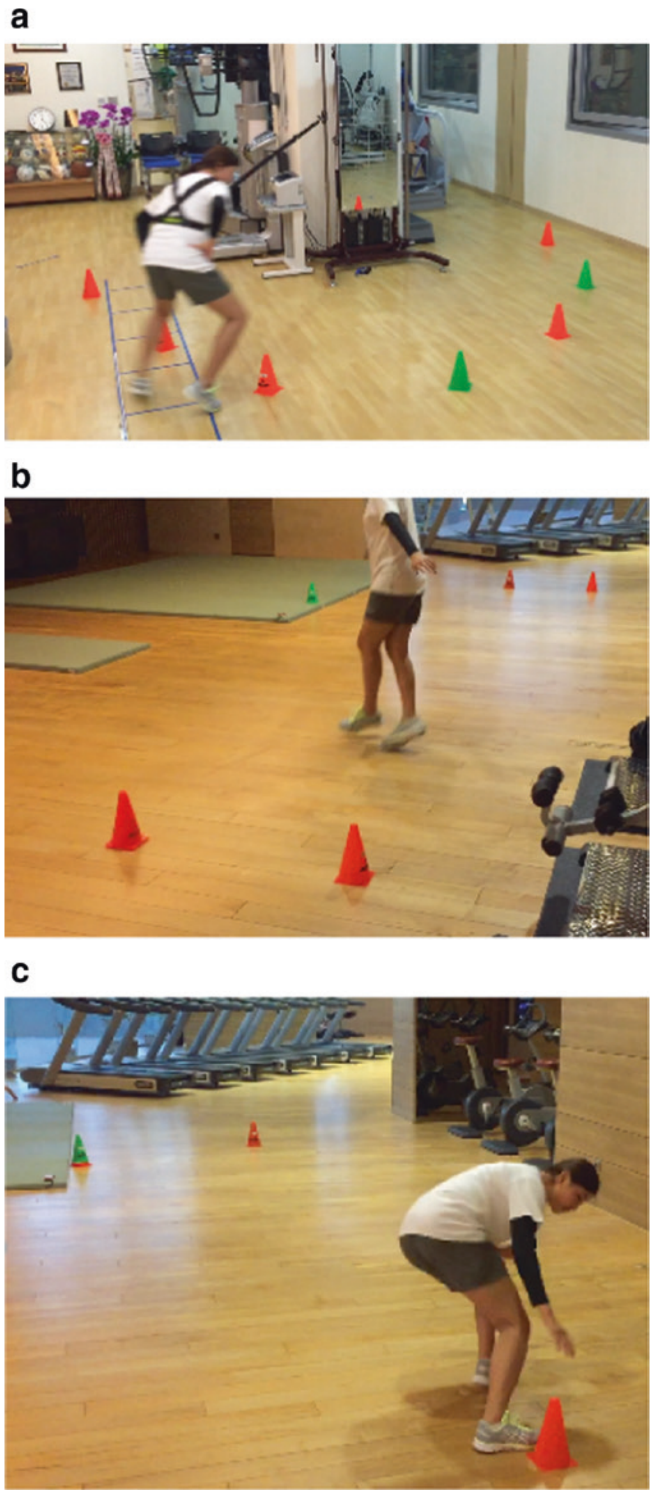

Fig. 4 **a** Co-contraction test. It reproduces the rotational forces of the knee joint. **b** Carioca test. It reproduces the pivot shift phenomenon on the tibia. **c** Shuttle run test. It reproduces the acceleration and deceleration forces on the knee joint

Fig. 5 Y-Balance test. It evaluates dynamic limits of stability and asymmetrical balance in three directions (anterior, posteromedial, and posterolateral)

by either the 3-year or 4-year follow-up after ACLR. Interestingly, they observed that a high fear index, indicated by a high TSK value, was strongly correlated with poor knee function. Chmielewski et al. [15, 16] reported that the TSK and functional parameters of the knee measured at 0–6 months of surgery, which is the postoperative recovery phase, did not show an association but the values measured during the rehabilitative phase (6–12 months of surgery) did.

Along with the TSK scale, another measure of psychological readiness for RTS after ACLR used by researchers is the ACL-return to sport after injury (ACL-RSI) scale [4, 12, 24, 51, 81]. Langford et al. [46] revealed that patients who returned to competitive sport at 12 months after ACLR had significantly higher score on the ACL-RSI scale than participants who did not. Research for the results of 7 different knee questionnaires which analyze all aspects of knee function in 164 patients after ACLR showed that psychological readiness to RTS measured using the ACL-RSI scale was most associated with returning to preinjury levels [2]. Recent study which evaluated the validation of the Knee Santy Athletic Return To Sport (K-STARTS) test including ACL-RSI scale reported that the K-STARTS test meets the criteria for validation as an objective test for RTS after ACLR [11]. They recommended that the test battery which includes both physical tests and psychological assessments (ACL-RSI scale) can give a more holistic evaluation of the patients' capacity to return to sports. Psychotherapy and confidence boosting for patients, as well as patient-centered health education, must be conjointly conducted after ACLR. Currently, the decision of RTS is often based on subjective questionnaires evaluating knee function, filled in by the patients themselves, but such approaches are restricted in that they cannot objectively assess patients' emotional factors, such as anxiety and confidence. Other forms of tests that effectively evaluate patients' emotional and mental status are required, for which interdepartmental collaboration between psychiatry and psychology departments is required to produce objective psycho-test items.

Conclusion

To improve the success rate of RTS after ACLR, clinicians have persistently conducted research and developed novel surgical treatments and rehabilitation protocols. Yet no standardized criteria exist enabling determination of the preparedness of patients to RTS in an objective and evidence-based manner. An objective and "goal-orientated" decision-making tool or a test battery that allows a functional and psychological assessment for decision-making regarding the safe return to sports is needed. The test battery that closely resembles the real sports activities under the dynamic and closed kinetic chain condition is required. To this end, various test batteries have been developed, and greater efforts are underway to produce simpler and more reliable forms. In the future, it is anticipated that developments and technological advancements in digital sensors and information technology will pave way to simpler test batteries that can measure real-time knee function. Additionally, because patients' emotional and mental states are important considerations in terms of deciding the feasibility or timing of RTS, psychological assessments should be conducted in conjunction with other physical tests.

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Anatomy and Function of the Posterior Cruciate Ligament

Jongkeun Seon

Abstract

The posterior cruciate ligament (PCL) consists of two functional bundles, an anterolateral bundle, and a posterolateral bundle. In general, the anterolateral bundle is taut in knee flexion, and the posteromedial bundle is taut during knee extension. The major function of the PCL is to resist posterior tibial translation relative to the femur, however, it also acts as a secondary restraint to resist varus, valgus, and external rotation in association with posterolateral corner complex.

Keywords

Posterior cruciate ligament · Anterolateral bundle · Posteromedial bundle · Anatomy · Function

Anatomy of the Posterior Cruciate Ligament

The posterior cruciate ligament (PCL) complex is composed of PCL and meniscofemoral ligament. The PCL originates from the lateral surface of the medial condyle and is attached to the PCL facet posteriorly, about 1.0–1.5 cm from the posterior tibial condyle, which has a depression behind and below the intra-articular portion of the tibia. The average length of the PCL complex is about 32–38 mm and the width is 13 mm. The cross-sectional area of the mid-substance is 31.2 mm^2, which is about 1.5 times larger than the ACL. The proximal part of the tibial attachment of the PCL is connected to the posterior horn of the lateral meniscus, and the posterior part is blended with the posterior capsule and periosteum.

Traditionally, the PCL is composed of two bundles, the larger anterolateral bundle (ALB) and the smaller posteromedial bundle (PMB) (Fig. 1), based on their femoral locations [1–3]. The anterolateral bundle is taut in knee flexion and the posteromedial bundle is taut during knee extension. PCL is an intra-articular structure but is considered as an extra-articular structure as it is covered by well-vascularized synovial membrane. This synovial sleeve contributes to its blood supply and the distal portion also receives some vascular supply from capsular vessels originating from the inferior and middle genicular arteries and the popliteal artery. Free nerve endings and mechanoreceptors have been identified in the femoral and tibial attachment sites and on the surface of the PCL [4, 5]. The mechanoreceptors resemble Golgi tendon organs and are believed to have a proprioceptive

J. Seon (✉)
Chonnam National University Hospital, Gwangju, Republic of Korea
e-mail: seonbell@chonnam.ac.kr

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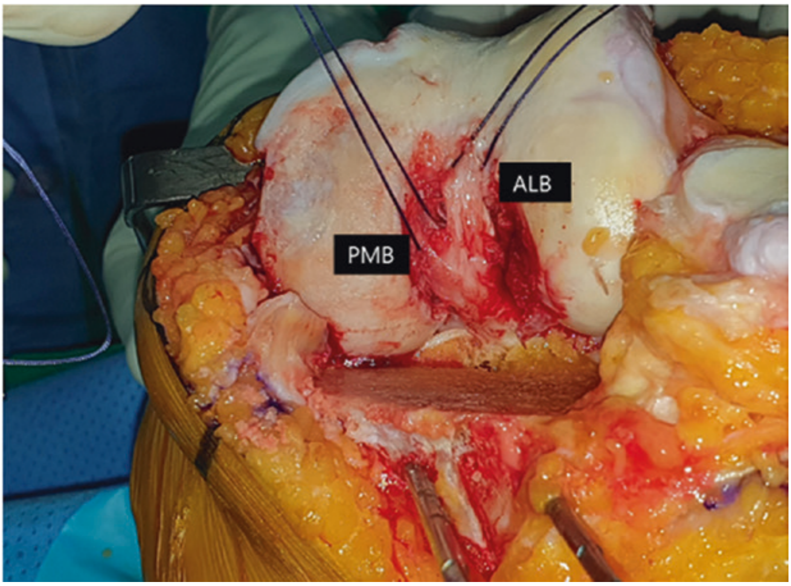

Fig. 1 PCL anatomy showing the anteromedial bundle (ALB) and the posteromedial bundle (PLB) A; femoral attach site, B; tibial attach site

function in the knee [6]. The meniscofemoral ligament originates from the lateral meniscus and is attached to the anterior portion of the medial femoral condyle, which is called as Humphrey ligament or posterior portion of the medial femoral condyle, which is called as Wrisberg ligament (Fig. 2). Recent studies suggest that at least one meniscofemoral ligament is present in 93% of the knees, the anterior meniscofemoral ligament (Humphrey ligament) in 74% of the knees, and the posterior meniscofemoral ligament (Wrisberg ligament) in 69% of the knees. The meniscofemoral ligament contributes to maintaining the harmony with PCL and posterior stability of the meniscus and the femoral head.

The Function of the Posterior Cruciate Ligament

The PCL is a primary structure that resists the posterior tibial dislocation to the femur in the knee flexion state and is responsible for 95% of the total load on the posterior dislocation [7, 8]. Also, it is a secondary structure that resists external rotation and varus and valgus [9–11]. Resistance to posterior dislocation during knee arthroplasty is mainly due to the posterior and posteromedial structures of the knee joint, while the primary resistance to external rotation and varus is due to the posterolateral complex (PLC). PCL consists of two functional bundles, an anterolateral bundle and a posterolateral bundle. Since the double bundle is a major functional bundle and accounts for about 85% of PCL bundles, it is a general principle to reconstruct an anterolateral bundle when performing single-bundle PCL reconstruction. The femoral attachment of PCL is three times wider than the medial parenchyma, thus creating difficulties in making an anatomic reconstruction. Also, there exists very little isometric fiber distribution in the center of the attachment of the femur, and in particular, most of the parts of the anterior and medial parts are nonisometric. A study on isometric reconstruction demonstrated that the posterior displacement of the tibia was restored at the initial flexion of the knee (0–45 degrees) and not at 45 degrees or more.

In a knee with a combined deficiency of the PCL and PLC, the abnormal posterior tibial

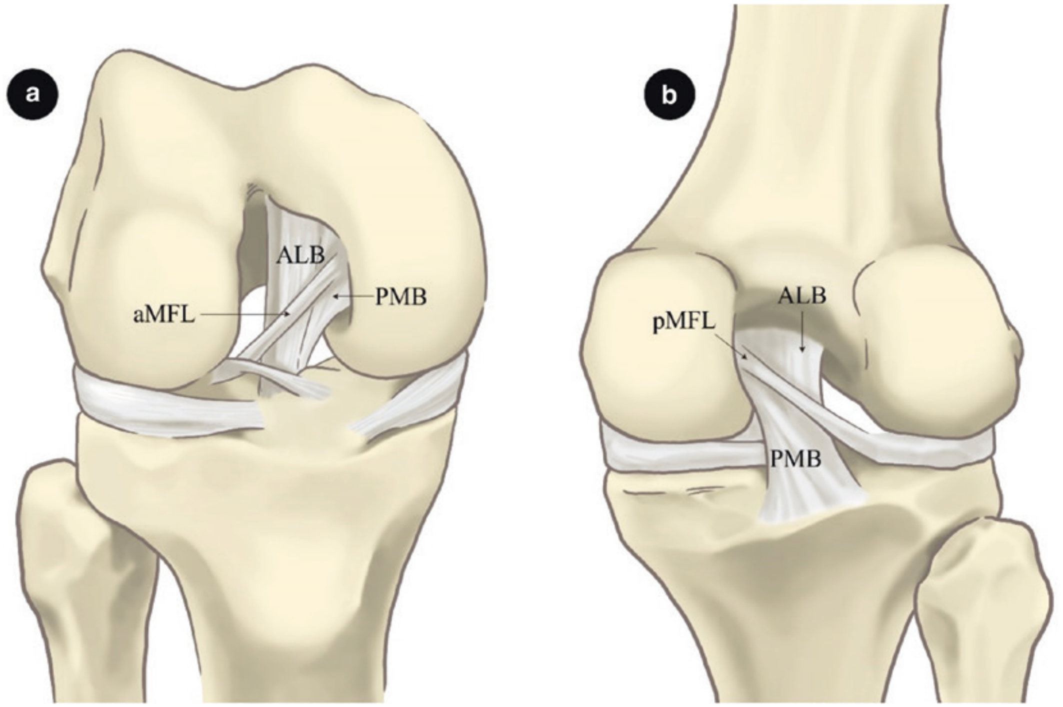

Fig. 2 **a** Anterior view of anterolateral bundle (ALB) and posteromedial bundle (PMB) of the PCL and anterior meniscofemoral ligament(aMFL). **b** Posterior view of anterolateral bundle (ALB) and posteromedial bundle(PMB) of the PCL and posterior meniscofemoral ligament(pMFL)

translation is at least four to five times the normal limit throughout the knee flexion. The abnormal forces placed on the patellofemoral and tibiofemoral compartments are expected to increase with the enhanced occurrence of posterior tibial displacement [12]. Skyhar et al. [12] stated that the pressure of the patellofemoral joint was significantly increased in the knee with injury to both posterior cruciate ligaments and posterior lateral complex and the medial pressure was significantly increased in the knee with isolated PCL injury. These results are consistent with the increased incidence of osteoarthritis in the patellofemoral and medial compartments in patients treated with non-surgical treatment of posterior cruciate ligament injuries.

The posterior cruciate ligament plays a role in stabilizing the knee joint in cooperation with the lateral collateral ligament and the sagittal ligament. In the experimental procedure about the excision of a ligament, the posterior dislocation of the tibia was increased during the knee flexion after the excision of only posterior cruciate ligament, but the dislocation level of the knee was significantly increased when the lateral collateral ligament and popliteus muscle were cut simultaneously. PLC injury results in increased lateral tibial opening and posterior subluxation of the lateral tibial plateau with external tibial rotation resulting in the positioning of the PCL at higher than normal load conditions. In general, PCL has small forces on both varus and valgus forces.

There are two primary restraints to external tibial rotation: the PLC at low flexion angles and both the PLC and PCL at high flexion angles. Increased external tibial rotation can occur in a combination of anterior dislocation of the medial tibial plateau, posterior dislocation of lateral tibial fixation, or both the subluxations. Consequently, the diagnosis of PLC injury should be based on the final position of the lateral tibial plateau rather than the increment of the tibia rotation.

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Posterior Cruciate Ligament Surgical Techniques

Ronald A. Sismondo, Christopher D. Hamad and Christopher D. Harner

Abstract

It is critical to understand the details and complexity of injuries to the posterior cruciate ligament (PCL) and associated structures to best design a successful treatment plan. Most isolated PCL injuries can be treated non operatively but complete PCL injuries associated with other ligaments usually require surgical intervention. Successful surgery requires a detailed knowledge of the anatomy, pathophysiology and skilled surgical techniques that reproduce the normal anatomy.

Keywords

Posterior cruciate ligament · Non-operative treatment · Anatomical insertions of the ligaments · Reconstruction · Associated injuries · Post-op rehabilitation

R. A. Sismondo (✉) · C. D. Hamad
6431 Fannin St, Houston, TX 77030, USA
e-mail: Ronald.A.Sismondo@uth.tmc.edu; ron.sismondo@gmail.com

R. A. Sismondo · C. D. Hamad
Department of Orthopaedics, The University of Texas Health Science Center At Houston, Houston, USA

C. D. Harner
Orthopaedic Surgeon, Pittsburgh, PA, USA
e-mail: harnercd1981@gmial.com

Introduction

As the previous chapter has discussed, the posterior cruciate ligament (PCL) has an important role in the normal function and kinematics of the knee. Treatment of posterior cruciate ligament injuries has been a topic of debate over time with a natural evolution as we have come to better understand its role and the nuances of treatment for this injury. Like all ligamentous interventions around the knee, the goals of treatment are primarily to restore or maintain normal joint kinematics and congruity. There have been multiple studies that show changes in knee kinematics and tibiofemoral contact areas in PCL-deficient knees [1–4]. PCL injuries also show increased cartilage injury over time particularly in the medial and patellofemoral compartments of the knee [5]. For these reasons, it is important to understand the various treatment of posterior cruciate ligament injuries and try to ensure the best possible outcomes for our patients.

As we begin to discuss in more detail the treatment options for these injuries it is important to remember three basic tenets. First, it must be understood that not all PCL injuries are the same. They come in all forms whether it be single bundle injuries versus double bundle injuries and injury to the meniscofemoral ligaments, complete versus partial injuries, or multiple ligament injuries to the knee. The latter is very important to remember as it is commonly the case that there is another ligament injured and

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this cannot be missed as this jeopardizes the outcome and can sabotage the otherwise thoughtful plan for treatment of the posterior cruciate ligament injury. In this vain, a full ligamentous exam of the knee should be performed on all suspected PCL injuries. The second tenet is that partial injuries do exist and that the PCL has the capacity to heal. Finally, the third tenet is that although isolated Grade II (6–10 mm of posterior translation as described below) injuries are not normal, they often function with minimal symptoms.

Non-operative Treatment

Prior to delving into the indications and techniques of operative treatment of posterior cruciate ligament injuries, we must first discuss non-operative management and its role in treatment as this is an important component to the overall treatment of PCL injuries. The posterior cruciate ligament is much different from its anterior counterpart in its inherent healing potential. As the posterior cruciate ligament is an extra-synovial structure it has the benefit of being in an environment which is more conducive to healing [6]. Also, the posterior slope of the tibial plateau is protective of the PCL during axial loading of the knee as it encourages anterior tibial translation of the tibial plateau [7–9]. This is the converse of anterior cruciate ligament (ACL) injuries where a high tibial slope is a known risk factor for tear as it increases load on the ACL [8, 10]. This aides in the treatment of these injuries as the general kinematics of the knee naturally offloads the ligament with axial loading.

Posterior cruciate ligaments are judged in severity by grade and this grading scale also helps to dictate treatment for these injuries and standardizes our discussion across the literature. Grading of injuries is based on the posterior translation of the medial tibial plateau in reference to the medial femoral condyle during a posterior drawer test (Fig. 1). The medial tibial plateau naturally sits approximately 10 mm anterior to the medial femoral condyle. The grading scale is as follows: Grade I 0–5 mm, Grade II 6–10 mm, and Grade III>10 mm.

In general, Grade I and II injuries are able to be treated non-operatively [11, 12]. Treatment of Grade 3 injuries is more controversial and often falls within the surgical realm so we will discuss those injuries in that section.

Our preferred method of treatment is a hinged knee brace or knee immobilizer locked in extension with full weight bearing allowed on the leg. As discussed previously, this allows for protective anterior tibial translational force with weight bearing. For combined PCL and posterior lateral corner injuries that will be treated non-operatively, we protect weight bearing on the extremity for 2 weeks to allow for early healing of the structures prior to progression to weight bear as tolerated. Exercises such as quadriceps sets, straight-leg raises, and calf pumps may begin in the first week. The patient may work with a physical therapist over the first month to achieve symmetric full hyperextension, and work on passive prone knee flexion. They may also work on quadriceps sets and patellar mobilization exercises. The brace is unlocked

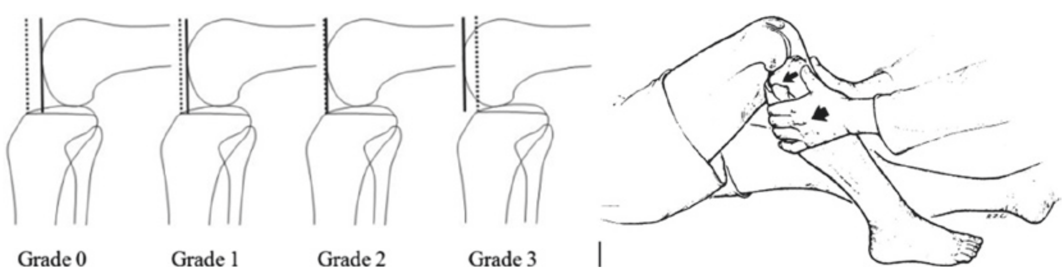

Fig. 1 Illustration of the posterior drawer test (right) where the knee is flexed to 90° and posterior directed force is applied to the tibia while feeling the step-off between the medial femoral condyle and medial tibial plateau. The amount of laxity is graded based on the relationship between the medial femoral condyle and medial tibial plateau (left). **This could be redrawn into a single diagram with the general design as the one above**

after 4–6 weeks to allow the patient to regain range of motion. The brace is typically discontinued after 6 weeks. The patient may progress to strengthening once full motion is achieved and he/she is otherwise asymptomatic. Closed chain exercises are preferred as this results in protective anterior tibial translation. Blood flow restriction therapy is also a consideration for patients prior to being able to advance to a formal strengthening program as this can help them maintain their muscle mass during that period of time.

An alternate to the hinged knee brace would be a dynamic anterior drawer brace which applies an anterior force on the tibia. This has shown promising results as well [13]. This can allow earlier motion of the knee throughout the initial phase of treatment.

Operative Treatment

Indications

Despite the majority of PCL injuries that are able to be successfully treated with non-operative intervention, there is still a large number of injuries which may benefit from operative treatment. This number is increasing with our understanding of the outcomes and natural history of these injuries and it is important to understand the indications of these procedures. Our current indications include displaced bony avulsions of either insertion, acute Grade III injuries with concomitant ligamentous injuries, acute isolated Grade III injuries in competitive athletes, and Chronic Grade II and III injuries with symptoms of pain or instability. Displaced bony avulsions should be repaired within 3 weeks of injury for the best results for anatomic repair [14–19].

Techniques

There are various techniques in the literature which can differ significantly, but the overarching goals remain the same to provide a functional reconstruction of the PCL and restore joint kinematics. The three main types of reconstructions include single bundle, single bundle augmentation, and double bundle reconstruction. There have been multiple studies comparing these techniques, particularly single and double bundle, and there are benefits to technique used. The other key technique difference lies in a transtibial tunnel versus a tibial inlay, but this often boils down to surgeon preference and comfort.

The single bundle technique recreates the anterolateral bundle which is the strongest and most robust bundle of the PCL [6, 17, 18]. Over time, the femoral tunnel has become the emphasis to become more anatomic to be placed in the anterolateral bundle footprint rather than a hybrid tunnel between the two bundle footprints. The single bundle technique is technically more straightforward and requires shorter operative time compared to double bundle techniques [17, 18]. As only the anterolateral bundle is recreated, this allows maximum graft size to be contributed to the strongest bundle. Although no difference in posterior translation is seen initially between double and single bundle techniques, over time, the single bundle technique often shows increased posterior translation compared with double bundle techniques [18]. Despite this laxity, there is limited and inconsistent evidence to suggest a clinical difference between the techniques [17]. Single bundle reconstruction may also offer a benefit for reconstructing multiple ligament injured knees as it minimizes tunnels created in the tibia and femur.

Single bundle augmentation is a variation on the single bundle reconstruction, where if intact, the posteromedial bundle and meniscofemoral ligaments are preserved. In our experience, it is much more common to have a remaining posteromedial bundle than an anterolateral bundle. The anterolateral bundle is reconstructed the same as it would be otherwise in the single bundle reconstruction. Preservation of the intact posteromedial bundle and meniscofemoral ligaments allows for maximal preservation of native kinematics and ligament function while helping to protect graft integrity as well. This has become our preferred technique over time as it offers the advantages of the single bundle reconstruction, but by preserving the posteromedial bundle, does not sacrifice its functionality.

When performing the single bundle augmentation technique, extra care should be taken to preserve the meniscofemoral and the intact PCL fibers. This is also the case when preparing the origin and footprint of the ligament. During graft passage, it is important to make sure the wire and passing sutures are in the right plane in relation to the intact PCL fibers and meniscofemoral ligaments so the graft does not get caught during graft passage or is not malpositioned.

The double bundle reconstruction technique seeks to recreate both the anterolateral and posteromedial bundles of the PCL. This technique shows better recreation of native kinematics in ex vivo biomechanical studies but has not consistently shown improved clinical outcomes compared to single bundle techniques [17]. During this technique, it is difficult to maintain the meniscofemoral ligaments if they are still intact at the time of surgery. When tensioning the graft, the anterolateral bundle graft is tensioned at 90° of knee flexion and the posteromedial bundle is tensioned in full extension.

Each of these techniques can be performed with transtibial or inlay techniques in the tibia. These techniques have not shown any clinical difference [15, 16]. One of the main debates regarding these two techniques is that transtibial techniques expose the graft to a sharp turn as they exit the tibial tunnel and course anterior toward the femoral insertion. This is often called the “killer curve” or “killer turn”. Some cadaveric testing has shown abrasion of the graft at this point, but no increased failures have been observed in patients. Also, it is important to consider that if a transtibial tunnel is used and the bone block is advanced to the tibial tunnel aperture at the tibial insertion the effect of this turn is mitigated. This allows the surgeon to use a transtibial drilling technique while gaining some of the benefit of the inlay technique in regard to the graft angle.

Graft Selection

Similar to other ligamentous reconstructions about the knee, there are various choices for graft available for posterior cruciate ligament reconstruction. Although decreased laxity over time has been reported with autograft, there has been no clear clinical difference between autograft and allograft. Common autografts used include quadriceps tendon with bone block (author’s preferred autograft), bone-patellar tendon-bone, and hamstring. Common allografts used include Achilles tendon (author’s preferred allograft) and quadriceps tendon.

For transtibial techniques, an 8–10 cm graft should be obtained. The graft can be slightly shorter depending on the tibial tunnel length. The bone block is placed on the tibial side despite the graft used. The graft is then fixed with the fixation of choice (suspensory versus interference fixation).

The senior author prefers to use a quadriceps tendon autograft with a bone block (Fig. 2) for competitive athletes and Achilles tendon allograft for non-competitive athletes. Also, the fixation of choice is suspensory fixation with a post on both the tibial and femoral side. This is sometimes modified to an inference screw in the femur.

Fig. 2 Quadriceps tendon autograft with bone block

Author's Preferred Technique

The senior author's preferred technique has evolved over the years. It began with non-anatomic single bundle reconstruction which quickly evolved to anatomic single bundle reconstruction. This was followed by double bundle reconstruction and finally single bundle augmentation. The latter three techniques are all utilized at different times depending on what is felt to be the right surgery for the patient. Whenever possible, single bundle augmentation is performed with preservation of the meniscofemoral ligaments and posteromedial bundle. Despite what approach is used, restoring native anatomy is paramount.

There are four basic principles followed at each PCL reconstruction procedure. First, examination under anesthesia, arthroscopic examination, and magnetic resonance imaging studies dictate the surgical approach and plan. Each one of these diagnostic modalities is important to understand the injury pattern and what is needed in regards to reconstruction. The second principle is that the posterolateral corner (PLC) is examined fully to ensure that there is no injury present. If so, this must be addressed or the PLC injury will increase the risk of graft failure [20, 21]. Third, the injury should be repaired/reconstructed acutely if possible. This is particularly the case with the posterolateral corner as after the first few weeks, the scarring of the area prevents adequate repair of the PLC structures. Finally, the anatomic insertion sites must be well understood for the structures of the suspected injury and planned repair/reconstruction.

The single bundle technique is utilized for acute injuries, and if there is a component of the native PCL and meniscofemoral ligaments remaining we proceed with single bundle augmentation. For chronic injuries where there is no remaining PCL component, we use a double bundle technique. As the single bundle and single bundle augmentation techniques are the most commonly used, we have outlined the author's single bundle technique in this chapter.

Each procedure begins with positioning in the supine position and a thorough examination under anesthesia. Before prep and draping of the patient the mini-flouroscope is used to ensure that an adequate lateral view of the proximal tibia can be obtained for later use when confirming tibial tunnel position. The mini-flouroscope can also be used during examination under anesthesia to judge posterior tibial displacement. No tourniquet is used. A pneumatic leg holder is used to support the leg in the preferred positions throughout the case. Alternatively, a bump is taped to the operating table to allow the knee to be held at 90 degrees and a post is used along the proximal thigh to support the leg.

Anterolateral and anteromedial arthroscopic portals are made with the lateral portal just along the lateral border of the patellar tendon inferior to the patella and the anteromedial portal approximately 1 cm medial to the patellar tendon. Diagnostic arthroscopy is performed to determine the extent of injury and assess the injured structures in the knee. In the notch, the PCL is examined for any remaining intact fibers and the state of the meniscofemoral ligaments. At this point, decision is made on whether it will be possible to perform single bundle augmentation versus single or double bundle technique. The damaged fibers are debrided with care taken to preserve the meniscofemoral ligaments and intact portion of the PCL which is usually the posteromedial bundle (Fig. 3). The footprint is also debrided with an arthroscopic shaver and electrocautery to better define the insertion site.

Following notch debridement, an accessory posteromedial portal is created to allow for access to the posterior compartment of the knee and to facilitate viewing and debridement of the PCL tibial footprint. This is performed under direct visualization with a 70° arthroscope which is passed through the notch from the anterolateral portal to more easily visualize the posteromedial aspect of the joint capsule. Once established, this portal can be used as either a working or viewing portal depending on need throughout the case. When viewing from the posteromedial portal, a 30° arthroscope is utilized. An appropriately sized arthroscopic cannula can be utilized to facilitate instrument passage through the portal.

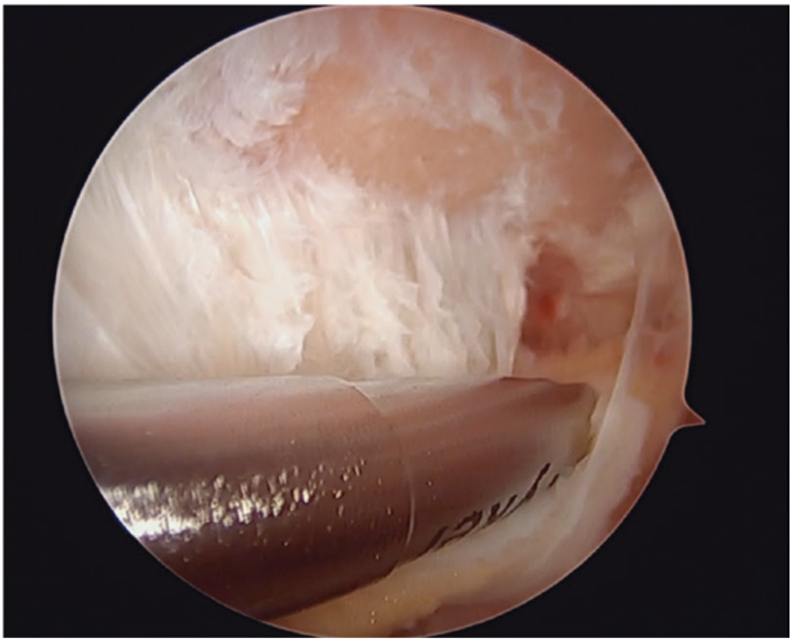

Fig. 3 Debridement of PCL remnant from anterolateral bundle footprint (left knee)

Appropriate visualization and adequate preparation of the PCL tibial insertion is paramount to safe tibial tunnel placement and drilling. To prepare the tibial insertion, a 70° arthroscope is utilized from the anterolateral portal to visualize the PCL footprint and a PCL curette is used from the anteromedial portal for initial debridement of the area. If needed, a fluoroscopic image can be obtained to confirm appropriate position. The arthroscope is then moved to the posteromedial portal (30° arthroscope) and a shaver is used from the anterolateral portal to debride synovium and elevate tissue from around the insertion. The arthroscope can then be moved back to the anterolateral portal and shaver placed in the posteromedial portal to allow for completion of debridement and exposure of the insertion. We then turn our attention to tibial tunnel drilling.

A PCL tibial drill guide is then placed through the anteromedial portal and placed slightly distal and lateral to the PCL tibial insertion. This is 15 mm distal to the articular margin proximally on the sloped PCL facet (Fig. 4). The correct position is then confirmed with fluoroscopy on the lateral view (Figs. 5 and 6). On the lateral view, the center of the PCL is approximately 70% of the distance along the PCL facet [22]. A guidewire is then advanced to the posterior cortex with the drill guide set on 55° (Fig. 7). The guide is then removed and a PCL curette is then placed through the anteromedial portal and is used to protect the structures traversing the posterior knee while the guidewire is advanced through the cortex. If the placement is not satisfactory, a parallel pin guide can be used to correct the position of the guidewire. A cannulated reamer is then used to drill the tunnel and tunnel dilators are to dilate the tunnel to the appropriate size.

If the patient is undergoing a concomitant anterior cruciate ligament procedure, the tunnels may be placed on the same(stacked) or opposite sides of the anterior tibia based on surgeon preference (Fig. 8). We prefer to place them on opposite sides of the anterior tibia with the ACL tunnel placed anteromedial and the PCL tunnel placed anterolateral. When placing the PCL tunnel anterolateral, the graft should be shortened 1–2 cm to accommodate the shorter tibial tunnel.

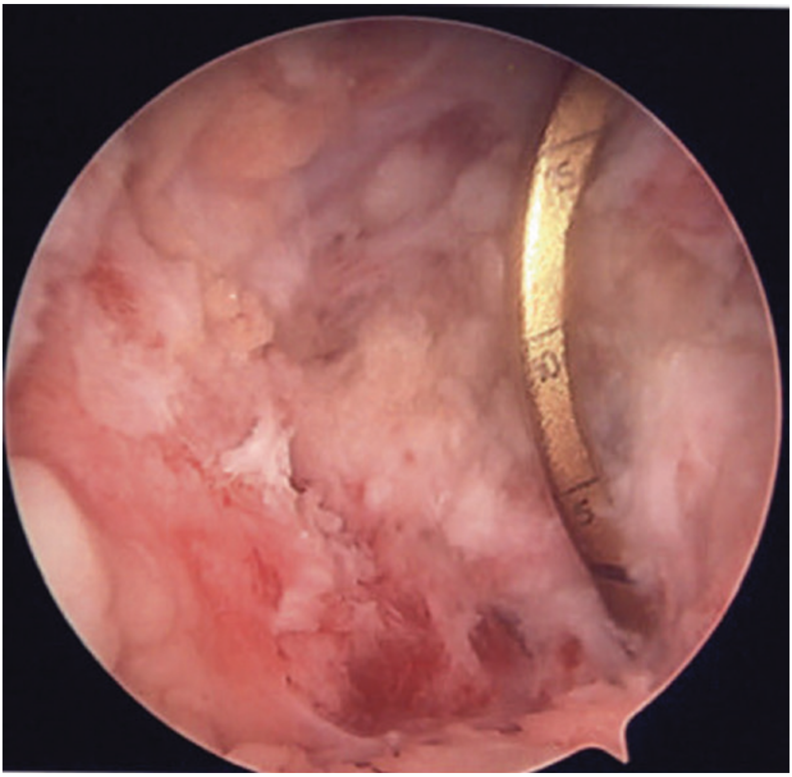

Fig. 4 View from the posteromedial portal showing guide placed on PCL facet (left knee)

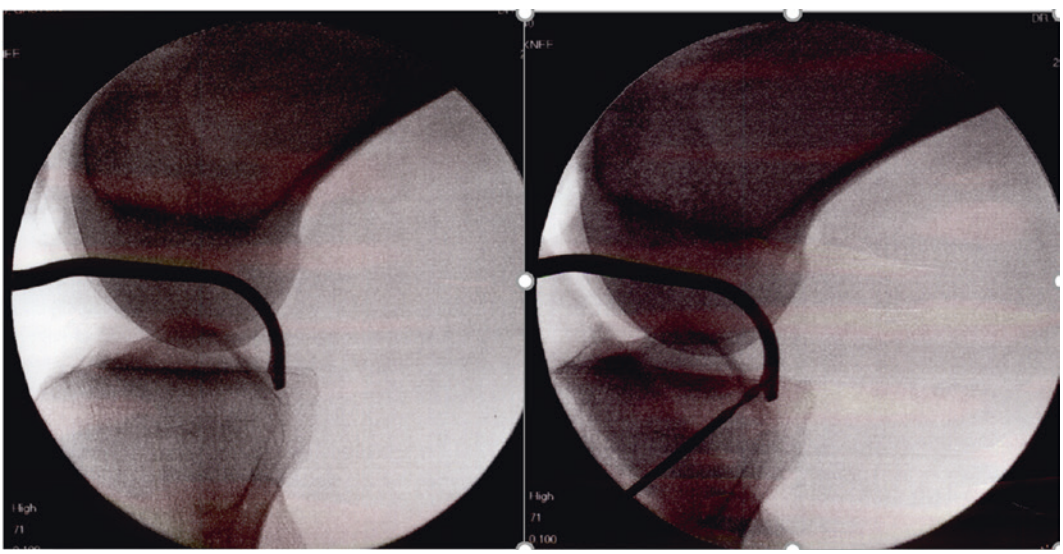

Fig. 5 Lateral fluoroscopic view confirming placement of the tibial drill guide (left) and guidewire placement for tibial tunnel drilling (right)

Fig. 6 Use of mini-flouroscope to confirm tunnel position (right knee)

Fig. 7 Tibial tunnel guidewire drilling. Arthroscope can be seen in the posteromedial portal. (right knee)

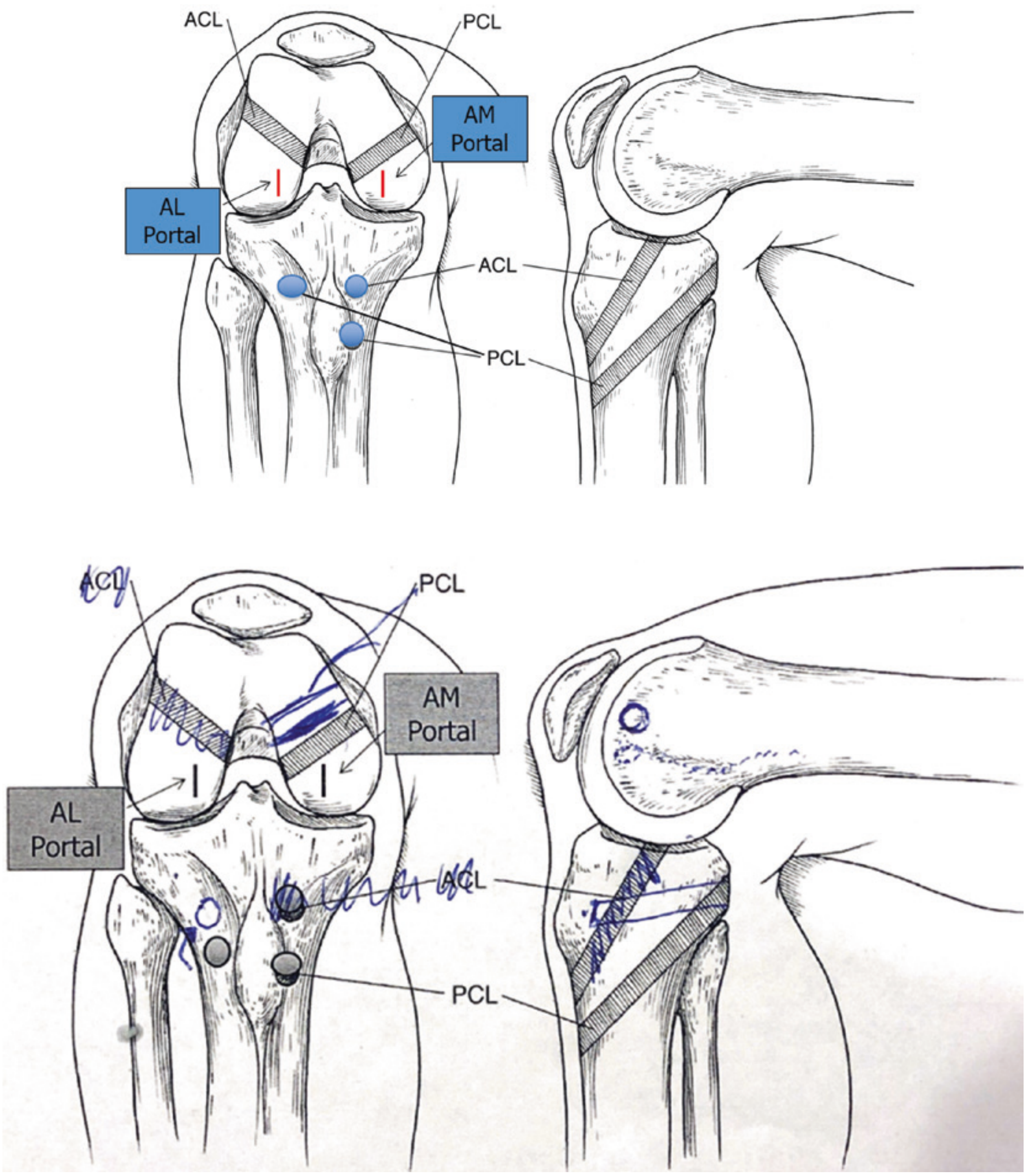

Fig. 8 Drawing depicting tunnel position for ACL and PCL grafts. Edits need to be made to the previous drawing to reflect changes below

Attention is then directed to the femoral tunnel. The tunnel is created through the low anterolateral portal (Fig. 9). An awl is passed through the anterolateral portal and the center of the planned tunnel is marked in the footprint of the anterolateral bundle of the PCL. The tunnel is positioned so the tunnel edge is located at the articular cartilage margin (Fig. 10). At 110° of knee flexion, a guidewire is advanced into the marked site and this is followed by a cannulated reamer. The socket is drilled to approximately 30 mm while taking care not to penetrate the outer cortex of the medial femoral condyle. Reaming of the tunnel is then followed by dilators

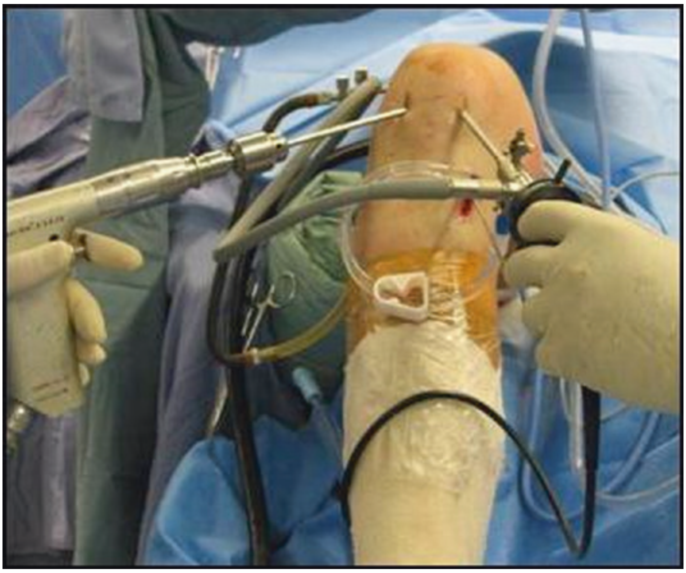

Fig. 9 Femoral tunnel drilling through a low anterolateral portal (right knee)

Fig. 10 Femoral tunnel position in the anterolateral bundle footprint just off of the articular cartilage margin (right knee)

up to the size of the graft. A smaller drill bit is used to perforate the outer cortex of the medial femoral condyle. An incision is then made over the expected exit site of the drill and dissection is carried down to the fascia of the vastus medialis obliquus (VMO). The fascia and subsequently the muscle is split in line with its fibers and dissection is carried down to bone. The periosteum is then split and elevated off of the bone to expose the drill hole and exiting guidewire.

The procedure of graft passage begins with an 18-gauge bent wire loop passed anterograde up the tibial tunnel with the arthroscope in the posterolateral portal. A tonsil through the anterolateral portal is then used to retrieve the loop through the notch. The free ends of suture from the tibial side of the graft are then passed through the loop and pulled back through the tibial tunnel. A small scopped malleable retractor is then used to retract the fat pad and provide a path for a Beath pin which is passed through the anterolateral portal and through the femoral tunnel cortex with the femoral side of the graft free sutures in the eyelet. Once these are retrieved the graft is passed into the femoral tunnel while pulling tension on the femoral sided sutures. The tibial-sided sutures are then tensioned and the graft is passed through the notch and into the femoral tunnel. The graft is being passed through the anterolateral portal during this step and it is important to note that before graft passage one should ensure that the anterolateral portal is large enough for graft passage. Once the graft is positioned in either tunnel and sutures preliminarily tensioned, the graft position is checked arthroscopically.

As mentioned previously, graft fixation is based on surgeon preference, but our preferred fixation is suspensory with a post on the tibia and femur. The femoral side of the graft is prepared with an Endoloop (Ethicon, Inc., Somerville, NJ) during graft preparation and prior to passage. After the passage of the graft, the endoloop is tensioned to determine its most proximal extent on the femur. This area is marked and a unicortical 6.5 mm screw and washer are placed through the endoloop for fixation. An anterior directed force is then applied on the proximal tibia for tibial tensioning and fixation. The graft is tensioned at 90° of knee flexion. A 4.5 mm bicortical screw with a washer is placed distal to the tibial tunnel aperture as a post and the graft is tied to the post (Fig. 11). The arthroscope is then placed back in the knee to confirm that the graft position, tension, and fixation are appropriate (Fig. 12). The knee should be taken through a range of motion to ensure that the knee range of motion is not limited by the graft. Wounds are then closed according to surgeon preference.

Post-operative Care

The post-operative plan for operative patients is similar to the course of treatment for non-operative injuries. Following surgery, the patient is placed in a hinged knee brace locked in extension which is continued for 4 weeks (Fig. 13). Patients begin to touch down weight bearing immediately and this is advanced to partial weight bearing after 1 week. Weight bearing is allowed as this results in anterior tibial translation which is protective for the graft. Within the first week, quadriceps sets, straight-leg raises, and calf pumps are begun. Under the supervision of a physical therapist to start, the patient works on regaining symmetric hyperextension, passive prone knee flexion, quadriceps sets, and patellar mobilization exercises in the first month. Anytime loading of the knee is performed, the focus should be placed on closed chain exercises. The brace is unlocked after 4–6 weeks and then discontinued at the 6-week mark. Throughout the post-operative period, the patient is closely followed in regard to motion with the goal of achieving 90° of knee flexion by 4 weeks and 110° by 8 weeks. The greater focus after posterior cruciate ligament surgery is on regaining flexion as in our experience, patients usually do not have difficulty achieving extension as they do after anterior cruciate ligament surgery. Once full range of motion is achieved the patient may progress to strengthening.

Complications

Like any surgical procedure, there are complications to consider that run the spectrum of severity. An important consideration during posterior cruciate ligament reconstruction surgery is the

Fig. 11 Post-operative X-rays depicting femoral and tibial fixation as wee as tunnel position and evidence of bone block harvest from the proximal patella

location of the neurovascular structures immediately posterior to the posterior capsule of the knee. These are in close proximity during multiple parts of the case particularly when working on the tibial insertion. Damage to these structures, especially the popliteal artery could be catastrophic. One must be vigilant during the surgery to protect this area at all times when working in the posterior knee.

The next consideration is in regard to tunnel malposition and graft tensioning. A malpositioned tunnel can act to limit range of motion, alter kinematics, and decrease graft function if not placed appropriately. This becomes more evident with the femoral compared to the tibial tunnel [22]. Improper graft tensioning can also result in limiting the knee throughout range of motion.

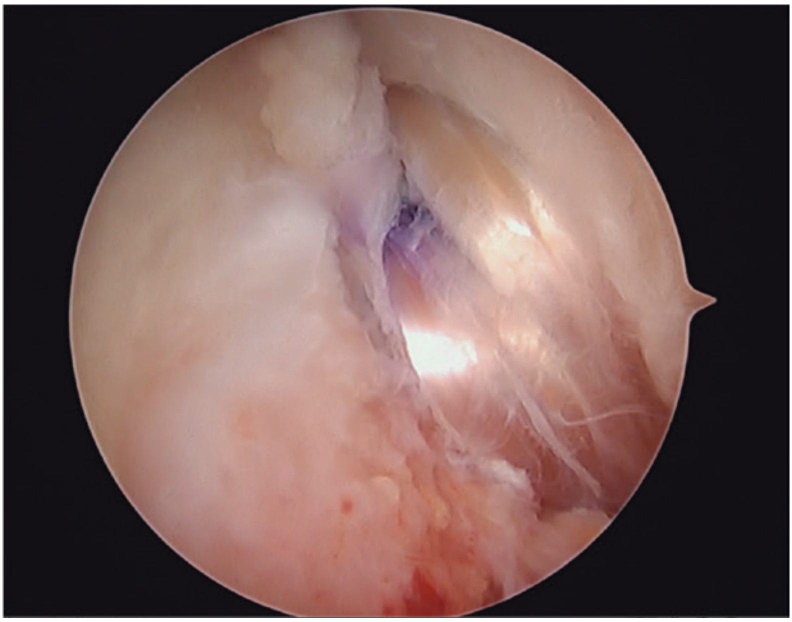

Fig. 12 Image of graft in place (Left knee)

Fig. 13 Hinged knee brace locked in extension

Post-operative stiffness must always be a consideration and monitored throughout the post-operative period. This becomes greater concern in knees with multiple ligament injuries. As mentioned previously, it has been our experience that flexion is the most difficult motion to regain following posterior cruciate ligament surgery. If a patient is having difficulty getting past 90° and has plateaued in regard to progress around 8 weeks, gentle manipulation under anesthesia is performed to get the patient past 90°. Once beyond that point, they are often able to regain the remainder of their range of motion with physical therapy.

Conclusion

Posterior cruciate ligament injuries are significantly varied in their presentation and do not tend to fit a "one size fits all" approach. There are many factors to consider and it is important to have a solid understanding of the available options in treatment and surgical techniques to find the right approach for the patient. It is important to keep a keen eye out for concomitant injuries as they can sabotage the patient's outcome if missed. Like any surgical procedure, it is important to understand potential complications and issues with the surgery and post-operative period so they can be avoided or at least minimized as much as possible and appropriately addressed when they arise.

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Combined Injury—Posterolateral Rotational Injury

Yong Seuk Lee

Abstract

Posterolateral rotational injury to the knee accounts for a significant number of knee ligament injuries, even though it is less frequently injured than the cruciate ligaments or other medial knee structures. Failure to detect these injuries may result in residual instability following cruciate ligament reconstruction, ultimately leading to graft failure and contributing to poor clinical outcome. The frequently occult nature of these injuries requires the attending surgeon to possess a high index of suspicion during the initial evaluation of the injured knee. Diligent and thorough history taking, physical examination, and radiographic studies are imperative to correctly identify these injuries. Treatment strategies range from conservative management to operative intervention. Operative management varies from tibial and fibular double sling technique to a single fibular or tibial sling. In this chapter we describe the anatomical single fibular sling technique for operative management of this injury, illustrating the key points with emphasis on critical surgical steps to achieve satisfactory clinical results. The postoperative rehabilitation protocols as well as potential complications are also discussed.

Keywords

Posterolateral · Rotational · Operative · Sling · Rehabilitation

Introduction

Posterolateral corner injuries are usually associated with other ligamentous injuries. These types of injury were frequently overlooked in the past [1] but are now widely acknowledged as a major contributing factor to poor results in the overall treatment process, particularly if there is a concomitant cruciate ligament injury [2]. Several physical examination, radiographic, and magnetic resonance imaging (MRI) tests have been developed to assess injuries to the posterolateral structures [3].

Y. S. Lee (✉)
Department of Orthopaedic Surgery, Seoul National University Bundang Hospital, 166 Gumi-ro Bundang-gu Gyeonggi-do, Seongnam-si, Republic of Korea
e-mail: smcos1@hanmail.net

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In this chapter, the anatomy, function, clinical and radiological evaluation, surgical technique, as well as the postoperative rehabilitation protocol of PLC will be discussed.

Anatomy

The lateral collateral ligament, popliteus, and popliteofibular ligament are equally important in posterolateral stability of the human knee. These unique structures limit primary posterior translation, primary varus and external rotation, and coupled external rotation [2, 4].

The lateral structures of the knee may be assigned to three distinct layers (Fig. 1). The most superficial layer (Layer I) includes the lateral fascia, the iliotibial band, and the biceps femoris tendon. Anteriorly, Layer II is formed by the quadriceps retinaculum, patellofemoral ligaments, and the patellomeniscal ligament. Layer III, the deepest layer, is the lateral part of the joint capsule. It also includes the popliteal muscle tendon unit and the lateral collateral ligament. The fabellofibular and arcuate ligament are formed in the deepest layer and vary in role of stability and size [5, 6].

Preoperative Considerations

Initial Evaluation

Patients with PLC injury show various manifestations depending on the severity of injury, instability, malalignment of lower extremity, and other concomitant injuries. In an acute injury, patients present with posterolateral swelling and pain at the posterolateral aspect of the knee [7, 8]. Frequently there is minimal swelling present even during an acute injury [8]. It is not uncommon for patients to complain of numbness and distal motor weakness secondary to injury to the sensory and motor branch of the peroneal nerve. The presence of these symptoms may give a clue to the extent of injury, indicating a significant varus or varus-rotational injury to the knee. Once the pain and swelling subside, patients may exhibit hyperextension of their knee during weight bearing ambulation. In chronic injuries, the knee hyperextension is more pronounced especially when climbing stairs. Posterior dislocation may also occur when they externally rotate their knee.

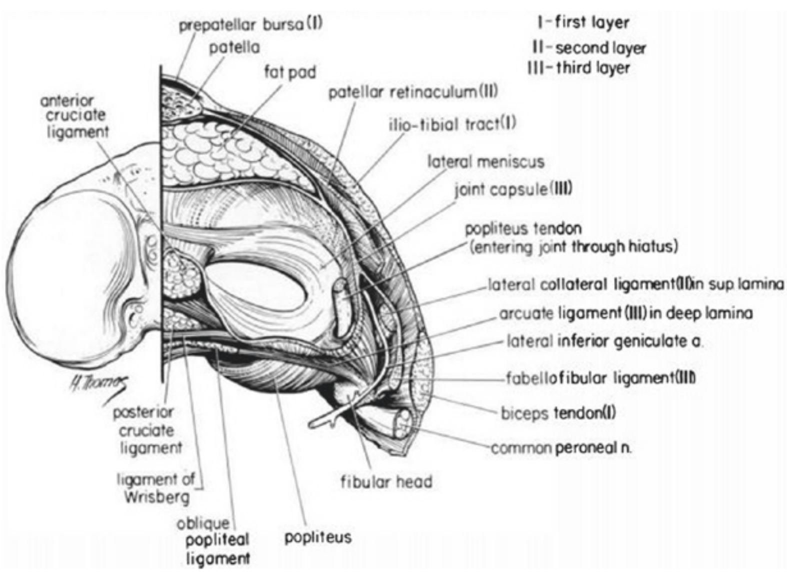

Fig. 1 The structure of the posterolateral aspect of the knee [5]

Physical Examination

Walking

Patients with PLC injury often complain of instability during normal walking, pivoting, twisting, or cutting to the affected knee. With concomitant cruciate ligament injuries, a more severe varus-thrust gait may be visible. There may also be complaints of instability on descending stairs, especially if there is a concurrent posterior cruciate ligament tear.

Inspection and Palpation

The injured knee should be examined thoroughly for swelling, ecchymosis, and tenderness over the posterolateral aspect especially after an acute event.

Sensory and Circulation Test

Examination of bilateral dorsalis pedis artery and posterior tibial artery pulses and comparison with the contralateral normal knee are mandatory. Other subtle signs that should be taken into account in an acute injury include skin temperature, color, and capillary refill should be documented. A thorough and complete neurological examination is performed, focusing on the common peroneal nerve due to the high prevalence of this associated injury.

Anterior and Posterior Translation Test

Assessment of the amount of anterior tibial translation on the Lachman test is important as well, which may be present in both an ACL-deficient or an ACL-intact knee. A solid end-point in an ACL-intact knee with an increased anterior translation on Lachman test ("pseudo-Lachman" test) may point to a possible underlying PLC or PCL injury (or both).

A posterior translation test in neutral rotation should be performed which may give clues to a suspected PLC injury. A slight increase in posterior translation of the knee at 30° but near normal at 90° flexion may indicate a PLC injury with an intact posterior cruciate ligament. If posterior translation at 30 and 90° are both significantly increased, a combined PCL and PLC injury should be suspected.

Dial Test

The dial test is commonly used to evaluate the PCL-PLC injury with settings of 30 and 90° of knee flexion [9]. The medial border of the foot is used as the reference measurement. Increased external rotation at 30°, but not 90°, indicates an isolated injury to posterolateral structures, whereas increased external rotation at both angles suggests injury to both posterolateral structures and the PCL [10, 11]. If external rotation of the injured tibia exceeds 10° in a side-to-side comparison with the uninjured tibia, posterolateral injury is suggested [10, 12]. The test can be performed with the patient in the supine position and an assistant applying an AP force to the tibia (Fig. 2) [13].

Posterolateral External Rotation Test

Patient is in a supine position with knee flexed at 90°. The examiner stabilizes the foot while grasping the femoral condyles. The tibia is externally rotated and a posteriorly directed

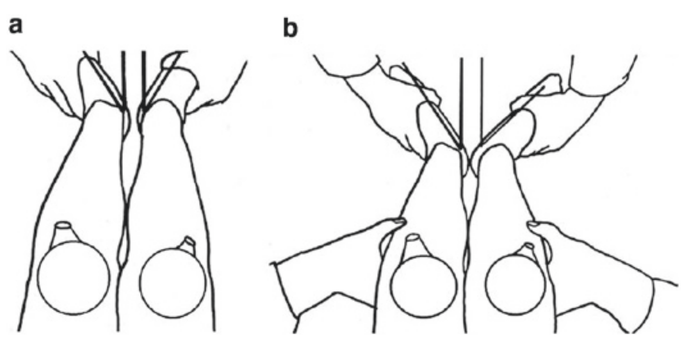

Fig. 2 Dial test. The thigh-foot and patella-tubercle angles were measured with external rotation stress applied to the tibia at both 30° and 90° of knee flexion. Before the torque was applied, a neutral force (**a**) and anterior force (**b**) were applied to the tibia [13]

force is applied. With injury to the PLC, there will be an increased translation with external rotation when compared to the contralateral normal knee. It is important to differentiate this test from the posterior drawer test in neutral rotation, which primarily assesses the integrity of the posterior cruciate ligament [14].

Reverse Pivot Shift Test

The patient is in a supine position with knee flexed at 90°. The examiner palpates and identifies the joint line, while applying a valgus and external rotation force to the tibia. While maintaining the valgus and external rotation stress, the knee is extended slowly. A positive finding is when a reduction of a previously subluxated lateral tibia is detected at approximately 35–40°. This corresponds to the iliotibial band function changing from a knee flexor to a knee extender upon extension of the knee. These findings should be compared with the contralateral normal knee.

External Rotation Recurvatum Test

This test is performed with the patient in supine position with both knees and hips in an extended position. While grasping the big toe, the examiner lifts the leg from the table with gentle pressure applied to the proximal knee. Measurement is performed in centimeters for the heel height or degrees of knee hyperextension, which is then compared to the contralateral side (Fig. 3).

Radiographic Evaluation

Although several physical examination techniques for the detection of posterolateral rotatory instability of the knee have been described, there is still no consensus with regards to the best method for objective documentation. Therefore, the role of radiographic evaluation in obtaining an objective assessment is of paramount importance. Plain radiographs in a knee with PLC injury may reveal concomitant periarticular fractures, avulsion fractures, foreign bodies, joint incongruity, and malalignment of the knee. Lower extremity alignment should be checked through X-ray of long bones and verify the necessity of valgus osteotomy.

The MRI is an indispensable tool in the assessment of ligament injury pattern. It also delineates other associated injuries including meniscal injuries, osteochondral lesions, and occult.

Operative Steps

Surgical Indication

Surgical indication is determined by the severity and time of the injury. Grade 1 or moderate Grade 2 posterolateral instability is usually treated conservatively. However, Noyes et al.

Fig. 3 Positive when the leg falls into ER and recurvatum when the lower extremity is suspended by the toes in a supine patient. (https://www.orthobullets.com/knee-and-sports/3003/history-and-physical-exam-of-the-knee)

reported residual mild laxity following conservative treatment of grade 2 injuries [9]. Grade 3 injuries to the posterolateral corner are best treated with surgery because the risk for continued symptomatic instability is significant.

Anatomical Posteriolateral Corner Reconstruction

There is little consensus as to the best technique for treatment because the PLC is a complex functional unit, which consists of several structures such as lateral collateral ligament (LCL), popliteofibular ligament (PFL), and popliteus tendon [15].

Several surgical techniques such as advancement of the osseous attachment of the arcuate ligament complex, proximal advancement of the PLC complex, biceps tenodesis, and the posterolateral corner sling (PLCS) have been developed to treat PLC injury and each of these techniques has had modest successs [16]. Nowadays, anatomical reconstructions are evolving in ligament reconstructions and it is believed that a restoration of an important structure to its original anatomy is the best method of reconstruction.

Described by LaPrade and colleagues in 2004 [17], this technique anatomically reconstructs the FCL, popliteus tendon, and popliteofibular ligament. Following a lateral approach and peroneal nerve neurolysis, the attachment sites of the fibular collateral ligament on the lateral fibular head and the popliteofibular ligament on the posteromedial fibular head are identified. An ACL-cannulated guide is then used to drill a guide pin from the FCL attachment on the lateral aspect of the fibular head posteromedially to the popliteofibular ligament attachment site (Fig. 4). This is overreamed with a 7-mm reamer. The posterior tibial popliteal sulcus is then identified with direct palpation in the interval between the lateral gastrocnemius and soleus muscles. This marks the musculotendinous junction of the popliteus. With a retractor protecting the neurovascular structures, an ACL-cannulated guide is used to place a guide pin from anterior to posterior. The pin is overreamed with a 9-mm reamer. The femoral attachment of the popliteus and the fibular collateral ligament

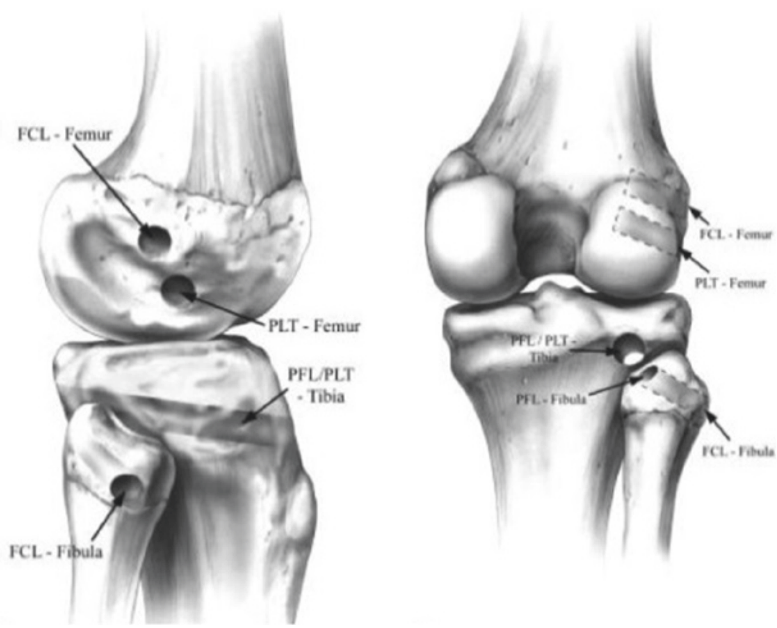

Fig. 4 The femoral, tibial, and fibular posterolateral knee reconstruction tunnel placement in a right knee [17]

are then identified. Eyelet pins are placed at their anatomic attachments sites and advanced anteromedially.

The distance between these two pins is measured and should be approximately 18.5–19 mm. The lateral cortex is reamed to a depth of 25 mm for both of these pins.

An Achilles allograft is split lengthwise and the tendons tubularized. Two 9- × 20-mm bone blocks are fashioned. Passing sutures in the bone block are used to reduce the bone blocks into the femoral tunnel and 7-mm metal interference screws are placed. The FCL graft is routed deep to the iliotibial band and through the tunnel in the fibular head. A 7-mm biointerference screw is placed with the knee in 20° of flexion, with a valgus force across the knee to reconstruct the fibular collateral ligament. The tail of the just placed FCL graft is continued to the posterior aperture of the popliteus tunnel, re-creating the popliteofibular ligament. Both the popliteofibular graft (the continued free tail of the FCL graft) and popliteus tendon graft are combined and routed through the tibial tunnel posteriorly to anteriorly and held in place with a 9-mm interference screw. The knee is flexed to 60° and an anterior force is placed across the tibia as the screw is advanced to complete the reconstruction (Fig. 5).

Anatomical Single Fibular Sling Technique

Incision and Approach

With the knee held in 90° of flexion, two separate 2–3 cm incisions are made over the epicondyle and fibular head. The iliotibial band is divided longitudinally. Two separate incisions are employed, whereby a transverse incision over the epicondyle and an oblique one over the fibular head are preferred. The direction of these two incisions coincides with the bone tunnels.

Tunnel Preparation

To complete the femoral tunnel, a guide pin is inserted at a point 5–7 mm anterior and distal to the apex of the lateral femoral epicondyle [16, 18] (Fig. 6). The taut Ethibond suture in

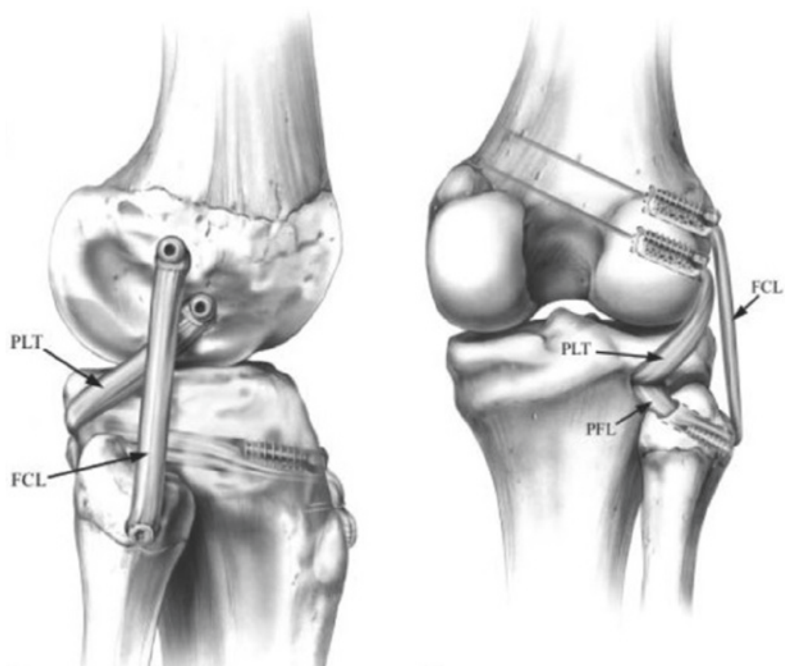

Fig. 5 The posterolateral knee reconstruction procedure [17]

the fibular tunnel is stretched till this guide pin for an isometric test using an isometer. Sutures placed in this way should have less than 3 mm strain changes.

To establish the fibular tunnel, the lateral collateral ligament (LCL) and the biceps tendon were first identified. In order to minimize the risk of injury to the peroneal nerve, dissection is either performed around the fibular head after releasing the peroneal muscle from the fibular neck, or, if the peroneal nerve could be visualized, it is isolated throughout its course around the fibular neck. A thin membrane exists between the LCL and the biceps tendon, and the tip of the guide pin is directed toward the area where the bare bone on the posterior surface of the fibular head could be palpated. The guide pin is drilled from an anteroinferior direction to the posterosuperior aspect of the fibular head (Fig. 7), following which a cannulated reamer of proper diameter is advanced over the guide pin [15]. Care is taken to avoid violating the proximal tibiofibular joint which may lead to bone breakage. Reaming with size 6 mm or above requires extreme care, particularly in small fibular heads, which are frequently seen in the Asian population. Injuries to the peroneal nerve may also occur during reaming. After an adequate tunnel is made, Ethibond No. 5 suture is passed through the tunnel to assess the isometric point and to facilitate graft passage.

Fixation of Grafts

Once the exact pin position is achieved, a cannulated reamer having the same diameter of the tendon graft is advanced over the guide pin. The edges of the tunnel openings are chamfered, and the grafts are pulled out first through the tunnels from the posterosuperior to the anteroinferior portal of the fibular head tunnel using

Fig. 6 To complete the femoral tunnel, a guide pin is inserted at a point 5–7 mm anterior and distal to the apex of the lateral femoral epicondyle and a cannulated reamer having the same diameter of the tendon graft is advanced

Fig. 7 To establish the fibular tunnel, a guide pin is inserted from an anteroinferior direction to the posterosuperior aspect of the fibular head

a No. 5 Ethibond suture loop. Both ends of the grafts are passed under the iliotibial band in a figure-of-eight pattern. The grafts' sutures are then advanced into the tunnel with the aid of slot-eyed guide pins. Preloading is performed approximately 20 times with an absorbable interference screw with the knee in neutral rotation and 70° flexion, with the foot supported (Figs. 8 and 9). This is in order to negate the effect of traction on the graft by the weight of the leg.

Rehabilitation

Postoperatively, with a concomitant PCL reconstruction, the knee is kept in full extension for 2 weeks, and weight bearing ambulation with crutches is allowed as tolerated. However, when both the ACL and PLC are reconstructed, the patient is allowed ROM exercise 3–4 days after surgery. In both cases, progressive ROM exercise occurs from 3 to 6 weeks. Progressive closed kinetic chain strength training was performed. The use of brace was discontinued after the 12th postoperative week.

Operative Risks and Complications

The fibular head tunnel method has several problems including fibular head fracture, peroneal nerve injury, infection, hematoma, stiffness, failure of reconstruction, hamstring weakness, irritation of fixator. The first two problems can be avoided by means of the techniques described previously. The presence of postoperative stiffness may necessitate manipulation or arthroscopic release under anesthesia.

Fig. 8 An absorbable interference screw is inserted in the fibular tunnel

Fig. 9 An absorbable interference screw is inserted in the femoral tunnel

Outcomes and Results

There is some controversy as to whether a tibia and fibular double sling technique or a single fibular or tibial sling is sufficient for reconstruction [17, 19, 20]. The single tibia sling method was first proposed by Albright and Brown [21]. The single fibular sling technique based on an isometric study was suggested by Fanelli and Larson [22]. Recently, Laprade et al. [17, 23] reported the tibia-fibular double sling technique as an anatomical reconstruction.

In this chapter, we described the single fibular sling technique, which is the author's preferred technique. Based on the author's experience, this anatomical reconstruction technique is simple, effective, and useful with satisfactory clinical results.

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Meniscal Injury and Surgical Treatment: Meniscectomy and Meniscus Repair

Ji Hoon Bae

Abstract

Meniscal tears are common injuries that may result in pain and functional limitation. Treatment options include benign neglect, rehabilitation, meniscectomy, and repair. Nonsurgical care can be used for older patients with degenerative meniscal pathology. Meniscectomy remains a viable and successful intervention for pain relief and functional improvement for symptomatic meniscal tears in appropriately indicated patients. However, it results in an increase in contact stresses in the articular cartilage of the affected compartment, leading to osteoarthritis. Meniscus repair provides improved long-term outcomes, better clinical outcomes, and less degenerative changes compared with meniscectomy. Orthopedic surgeons should know the proper indications of meniscus repair and understand various techniques and surgical devices for the management of repairable meniscal tears. A new technology of biologic augmentation for better healing and tissue engineering for meniscal defect is currently developing, and they may help the management of complex meniscal tears in the future.

Keywords

Meniscectomy · Repair · Biologic augmentation

The meniscus has an important biomechanical role in the normal function of the knee including load bearing, shock absorption, and joint stability [32, 73]. The larger contact area provided by the meniscus reduces the average contact stress in the knee joint. The menisci thus prevent mechanical damage to articular cartilage. Tears of the meniscus are one of the common knee injuries and more than one-third of people over the age of 50 years have meniscal pathology detectable on MRI. As orthopedic surgeons frequently encounter patients with asymptomatic or symptomatic meniscus tears, they should know the current evidences of nonoperative, meniscectomy and meniscus repair to determine the optimal treatment strategy. In this chapter, the author provides a practical guide about the management of meniscus tears and describes the arthroscopic techniques of meniscectomy and meniscus repair.

Clinical Evaluation

A detailed, careful, systemic clinical evaluation is important to not only determine whether current symptoms and functional limitations result

J. H. Bae (✉)
Department of Orthopedic Surgery, Korea University Guro Hospital, Korea University College of Medicine, Seoul, Republic of Korea
e-mail: osman@korea.ac.kr

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from a torn meniscus but also to select the most proper treatment between nonoperative, meniscectomy and repair. Disorders that can produce symptoms similar to those of a torn meniscus must be kept in mind to avoid misdiagnosis and improper treatment. A thorough history includes the presence of trauma, assessment of the injury mechanism, initial and current symptoms, preinjury occupational and sports activity levels and current functional limitations. The history of specific injury may not be obtained, especially when tears of abnormal or degenerative menisci have occurred. This scenario is noted most often in middle-aged patients who sustain a weight-bearing twist on the knee or who have pain after squatting. Tears of normal menisci usually are associated with more significant trauma or injury but are produced by a similar mechanism: the meniscus is entrapped between the femoral and tibial condyles in flexion, tearing as the knee is extended. Patients with tears in degenerative menisci may recall symptoms of mild catching, snapping, or clicking, as well as occasional pain and mild swelling in the joint. Once the tear in the meniscus becomes of significant size, more obvious symptoms of giving way and locking may develop. A comprehensive physical examination is performed, which includes the presence of swelling or effusion, knee range of motion, tibiofemoral joint line tenderness, diagnostic tests such as McMurray test, Apley test, squat test, ligament instability, muscle atrophy, and gait abnormalities. Plain radiographs including full standing lower limb, weight-bearing posteroanterior at 45° of knee flexion, lateral at 30° of knee flexion, and patellofemoral axial provide limb alignment, joint space narrowing, patellofemoral joint problems. Coronal lower limb alignment is measured using full standing hip-knee-ankle weight-bearing radiographs in knees that demonstrate varus or valgus alignment. MRI provides not only information about meniscus tear types and integrity based on signal patterns but also concomitant ligament and articular cartilage injuries. However, the final decision between meniscectomy and repair is not made until the time of diagnostic arthroscopy in some patients.

Treatment Decision

Treatment should be individualized in a shared decision-making process with the patient after discussion about known outcomes. The patient age, activity level, expectation, meniscus tear type, tear location, tear size, associated degenerative changes, concomitant other injuries, and the presence of malalignment are important considering factors when determining proper treatment [11, 23, 35, 50, 63]. Symptomatic degenerative tears or tears with minimal healing potential are mostly treated with nonoperative or meniscectomy. Meniscus repair should be considered when there is high possibility that the meniscus will heal and maintain function [35]. Arthroscopic meniscectomy to manage the unstable meniscal tears with mechanical symptoms may be beneficial, especially in a patient who fails to respond to nonoperative treatment. However, the available evidence suggests that surgical treatment should not be the first-line intervention for patients with meniscal tears who are in middle or old age [1]. The ESSKA Meniscus Consensus Project developed a decision-algorithm for these patients [10]. In painful knee in middle-aged subjects, plain radiographs should be taken in first line. MRI is not indicated at this stage, unless a diagnosis requiring complementary examination is suspected. Nonoperative treatment is initiated, comprising physiotherapy and possibly intra-articular injections. Only in case of failure at 3 months following nonoperative treatment, MRI is performed to confirm the diagnosis of the degenerative meniscal lesion or otherwise, although it is still necessary to check that the lesion matches the symptoms. If radiographs and MRI show no signs of advanced osteoarthritis, and notably of meniscal extrusion or facing chondral edema, arthroscopy may be considered. On the other hand, osteoarthritis, when revealed, is to be treated in first line, arthroscopic debridement showing no superiority. The presence of “considerable” mechanical symptoms constitutes a special case, in which early arthroscopic treatment may be indicated.

Nonoperative Treatment

Acute or chronic meniscal tears with infrequent or minimal symptoms can be treated with strengthening exercises and activity modification. Partial thickness tears or small stable (1 cm long or less, less than 3 mm displacement from periphery) tears in vascular zone found during diagnostic arthroscopy, also can be treated nonoperatively, if the knee is stable [30, 49, 64, 85]. However, the patient must be informed that any tear in the meniscus may not have healed or symptoms recur despite strengthening exercise and activity modification. If symptoms recur or worsen after nonoperative treatment, surgical treatment may be necessary.

Fig. 1 Coronal MRI images showing inferiorly displaced medial meniscus fragment into the medial gutter

Operative Treatment

Acute meniscal tears causing a locked knee or chronic tears with a superimposed acute meniscal injury in a patient with a history of symptomatic episodes such as catching, locking, and giving way are likely to require operative management. It is important to discuss with the patient the benefits, risks, and outcomes of meniscectomy and repair, as well as the rehabilitation program, time of return to daily activities, work, and sports [73]. As activity restriction following meniscus repair takes longer when compared with meniscectomy, the surgeon should judge the willingness and the ability of the patient to comply with required postoperative restrictions. The patient is informed that the final procedure can be changed intraoperatively according to arthroscopic findings, and the rehabilitation program may require modification according to the final procedures performed. When meniscectomy is planned, displaced torn meniscal fragments are carefully identified by MRI (if taken) preoperatively to avoid insufficient resection intraoperatively (Fig. 1). In addition, surgeons should figure out which portion of the meniscus is resected or preserved to maintain meniscus function as possible. If a torn meniscus is potentially repairable, it is important to figure out what repair techniques are most proper and check all of the instruments available in the operating room.

Meniscectomy

Indication

A meniscectomy is indicated for acute or chronic irreparable meniscal tears causing recurrent symptoms and significant functional limitation, although an adequate nonoperative treatment is performed for more than 3 months [1, 41]. Chronic displaceable vertical longitudinal or bucket handle tears, radial or oblique tears confined to white-white or red-white, and horizontal flap tears are common tears managed with meniscectomy (Fig. 2). The patient should be informed that symptoms may not be resolved quickly, or residual symptoms may remain even after well-performed meniscectomy.

Patient Position and Diagnostic Arthroscopy

The patient is placed in the supine position on the operating table so that the affected leg is

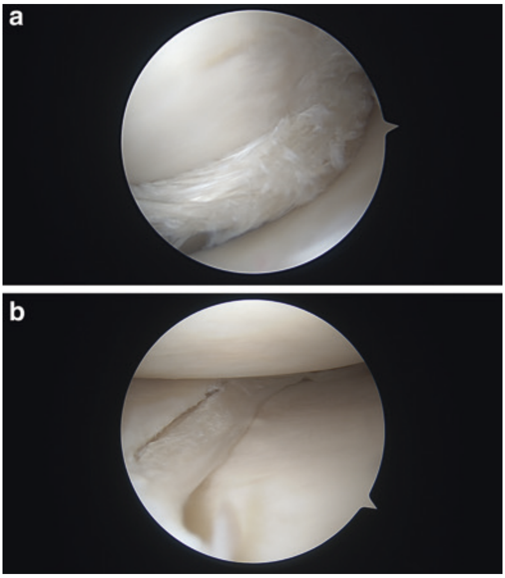

Fig. 2 **a** Chronic bucket handle tear of the medial meniscus, **b** chronic small vertical longitudinal tear of the medial meniscus, radial tear of the lateral meniscus extended to red-white zone, displaced flap fragment of the medial meniscus posterior horn

elevated. The knee is positioned distal to the edge in the table, allowing posteromedial or posterolateral access if the foot of the table is flexed or removed during the procedure. A tourniquet is placed on the proximal thigh, and a lateral thigh post is set to apply a valgus stress to improve visualization of the medial compartment. The anterolateral portal is placed adjacent to the patellar tendon 1 cm above the joint line and 1 cm lateral to the margin of the patellar tendon. A 30° arthroscope is gently inserted into the joint through the anterolateral portal with the knee in 70° to 90° degrees of flexion and then advanced toward suprapatellar pouch with a knee extended. A systematic examination is performed from the suprapatellar pouch through the medial gutter, medial compartment, intercondylar notch, lateral compartment to lateral gutter. With the arthroscope focused in the medial compartment, the anteromedial portal is created with the aid of a spinal needle. Depending on the location of the meniscus tear, the anteromedial portal can be adjusted appropriately for easy access. Precise working portals are very important to resect the meniscus as planned and to avoid the damage of the articular cartilage by instruments. Too high anterior working portals make it difficult to access the posterior horn of the meniscus. After systemic examination of the knee joint, one palpates carefully the superior and inferior surface of the tear site of the meniscus using a probe to determine the type and extent of the meniscal tear and to find any displaced unstable meniscal fragment. Failures to classify accurately the extent, various planes of the tear and failure to find the displaced unstable meniscal fragments often results in insufficient resection or removing healthy meniscal tissue. If the medial compartment is too tight to view the posterior horn of the meniscus, release of the medial collateral ligament by pie-crusting can increase the space of the medial compartment [26, 31]. To examine the posteromedial compartment, a 30° arthroscope is advanced obliquely from the anterolateral portal through the intercondylar notch between the posterior cruciate ligament and the medial femoral condyle to the posteromedial compartment. If the gap between is the posterior cruciate ligament and the medial femoral condyle too narrow to advance, a valgus stress in a 30° of knee flexion help advance the arthroscope. For examination of the posterolateral compartment, a 30° arthroscope is advanced obliquely from the anteromedial portal through the intercondylar notch between the anterior cruciate ligament and the lateral femoral condyle to the posterolateral compartment. Usually, introducing an arthroscope to posterolateral compartment is easier than posteromedial compartment. If the gap between the anterior cruciate ligament and the lateral femoral condyle is tight, the figure four position makes an arthroscope advance easier. With a 30° arthroscope through anterior portals, it may be difficult to view around the posteromedial or posterolateral corner. Instead, a 70° arthroscope through the anterior portals is useful for investigating around the posteromedial or posterolateral corner.

Arthroscopic Meniscectomy Techniques

No standard techniques of meniscectomy are present, but the following principles are kept in mind: (1) preserve the meniscus as much as possible to maintain its function, (2) remove completely the unstable meniscal fragments causing symptoms and confirm there are no hidden tears before finishing the operation, (3) frequently probe an edge of meniscus during meniscectomy and leave a contoured, balanced, stable peripheral rim finally, (4) the instruments and the meniscus to be removed are always within the arthroscopic view to avoid damage or resection of normal healthy structures, (5) use an accessory portal if needed, (6) suction to remove any morselized meniscal fragments, which may cause synovitis later.

Meniscectomy can be performed either with one-piece resection of the large, mobile fragment such as displaceable large bucket handle tears or bit by bit resection of the non- or partially displaceable small- to medium-sized meniscal fragments such as small longitudinal tears, horizontal flap tears, incomplete radial tears, and complex tears. Small mobile meniscus fragments also can be removed by a motorized shaver. If one-piece resection of bucket handle tear is planned, resection of the posterior attachment first is preferable, because the meniscal fragment can be displaced in the posterior compartment after anterior resection and a large floating meniscal fragment in the intercondylar notch can limit an arthroscope and basket forceps access to the posterior attachment. An accessory anterior portal may be useful to grab and pull the displaceable meniscal fragment during resecting the anterior or posterior attachment through a standard portal. This also prevents the meniscus from floating freely during resection of the meniscus attachment. For horizontal flap tears or complex tears, surgeons should probe the tear site of the meniscus carefully to find any flap fragment. A flap often comes from the inferior leaf and it can be rolled up under the meniscus or inverted behind the femoral condyle (Fig. 3). When a flap fragment is displaced in the posterior compartment,

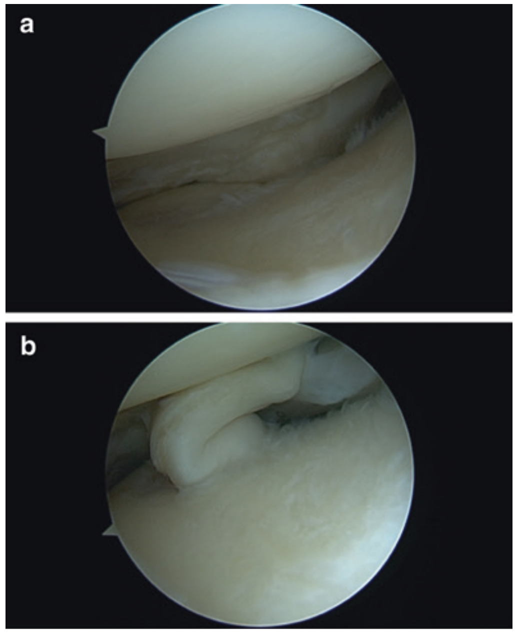

Fig. 3 **a** A flap fragment rolled up under the lateral meniscus posterior horn, **b** after pulling the rolled meniscal fragment

additional posteromedial or posterolateral portals may be required to remove [36]. The superior and the inferior leaves are resected back to a relatively stable peripheral rim. When the horizontal tears in the anterior horn are resected, inframeniscal portals or a joystick technique can be useful to remove torn inferior leaves of the anterior horn, because the basket forceps or a shaver are difficult to reach the anterior horn through the anterior portals (Fig. 4) [44, 45, 55, 61]. Incomplete radial tears (mostly occurs at the midbody or posterior horn of the lateral meniscus) can be resected a bit by bit by basket forceps to the end point of a tear. It should be careful not to over-resect the anterior and posterior portion of the meniscus during balancing and contouring the rim.

Outcomes of Meniscectomy

Clinical outcomes following meniscectomy are dependent on multiple factors. Current studies suggest that many patients with a high preinjury activity level, younger age, medial

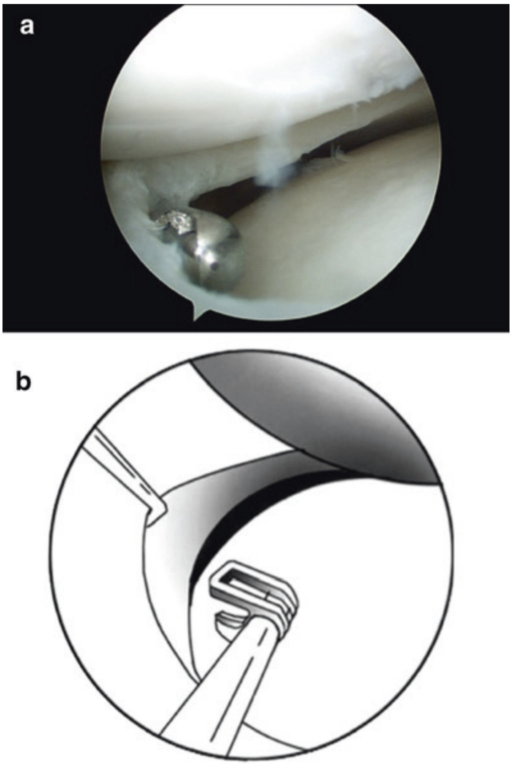

Fig. 4 **a** Resection of anterior horn of the lateral meniscus using a motorized shaver through the inframeniscal portal, **b** joystick technique, a nerve hook through the far anteromedial portal (Permission from Arthroscopy Vol 20, No 6 (July-August, Suppl 1), 2004: pp 146–148, Fig. 5

meniscectomy, and smaller meniscal resection are more likely to return successfully to activities and sports following partial meniscectomy, although not always at their preinjury level of activity [32, 73]. Improved clinical outcomes can be expected for male patients without obesity who are undergoing medial meniscectomy with minimal meniscal resection. Varus or valgus deformities, preexisting degenerative changes in the knee, and anterior cruciate ligament deficiency negatively influence outcomes following meniscectomy. Failure rates following meniscectomy are relatively low compared with meniscal repair and discoid saucerization, although revision rates are increased in patients undergoing lateral meniscectomy. Meniscectomy increases the risk of developing knee osteoarthritis (OA), particularly in female patients with obesity who undergo large meniscal resection and with that so does the risk of progressing to TKA.

Meniscus Repair

Indication

Best indications for meniscal repair are a traumatic vertical longitudinal tear or bucket handle tear in the vascular zone of the meniscus, and meniscocapsular junction tear (Ramp lesion) concomitant with an acute ACL tear (Fig. 5). A radial tear that extends to the periphery of the meniscus and horizontal tears in young patients also can be considered. A lower rate of healing is expected in a tear that is located at the white-white zone. Patient factors including age, activity level, rehabilitation potential, limb alignment, ligament stability, and degenerative changes of joint also must be considered.

Arthroscopic Repair Techniques

Arthroscopic repair techniques include the inside-out, outside-in, and all-inside techniques. The inside-out or outside-in meniscus technique is still used by many surgeons to repair the torn meniscus, whereas all-inside repair devices are becoming much more popular currently as the result of their ease of use. Regardless of the repair techniques, there are important principles for successful healing: (1) consider patient factors (age, activity, expectation, willingness for rehabilitation) (2) tear debridement and local abrasion to stimulate a healing response, and (3) meticulous suture placement to reduce anatomically and stabilize the meniscus during healing process [12, 23, 35].

Inside-Out Technique

The inside-out technique is traditionally considered the gold standard for the meniscus tears involving the middle thirds and/or the

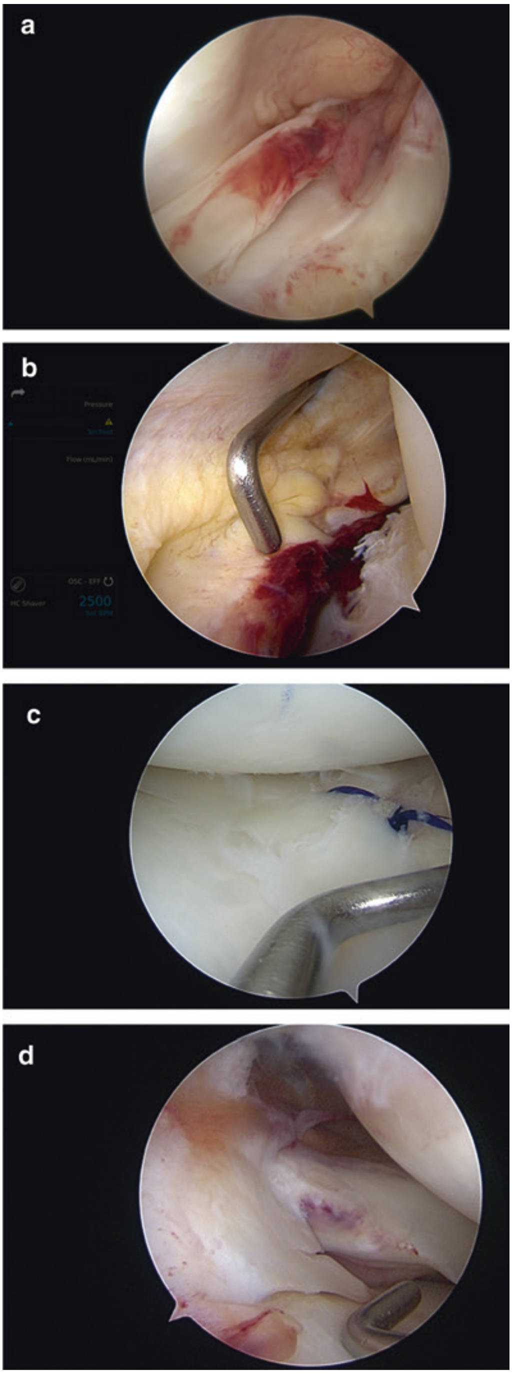

Fig. 5 **a** Acute bucket handle tear of the medial meniscus, **b** acute ramp lesion of the medial meniscus combined with an ACL tear, **c** radial tear of the lateral meniscus extended to red-red zone with one vertical suture, **d** acute oblique tear near to the posterior root of the lateral meniscus

posterior horn. Advantages of this technique are the precise placement of sutures in a various configuration (vertical, horizontal, oblique, cross). However, there is a risk of neurovascular injuries, so an additional posteromedial or posterolateral exposure is required to protect the neurovascular structures when repairing the posterior horn tears [22]. For inside-out repair, various angled zone-specific suture cannulas (Fig. 6) and a 10-inch flexible straight double arm needle attached with 2-0 braided nonabsorbable sutures are required.

Arthroscopic Inside-Out Technique for a Longitudinal Tear of Midbody and Posterior Horn of the Meniscus

A valgus (with 20-30 degree of knee flexion) or varus stress (usually figure four position) helps open the medial or lateral compartment to access the posterior horn. A 30^{o} arthroscope is inserted through the anterolateral or anteromedial portal according to the tear site. The zone-specific suture cannula is introduced through the anterolateral or anteromedial portal and pointed to the exact location of suture placement. A radius of suture cannula should be not only large enough to angle the needle away from the neurovascular structures posteriorly but also pass the needle through the tear vertically. Occasionally, the tibial spines block access for the suture cannula and an accessory portal may be required. If a tear involves the posterior horn beyond the posteromedial corner (in this case, the author prefers all-inside repair using a suture passer hook through the posteromedial portal), a posteromedial exposure is needed to protect the neurovascular structures (Fig. 7a). A 3 to 4 cm vertical skin incision is made over the posteromedial aspect of the knee and then the interval between the medial head of the gastrocnemius and the posterior capsule is identified. A retractor is placed in this interval to protect the neurovascular structures and to help capturing the needles. The tip of the cannula is placed in a fashion that the needle enters the inner side of

Fig. 6 Zone-specific cannulas for inside-out repair

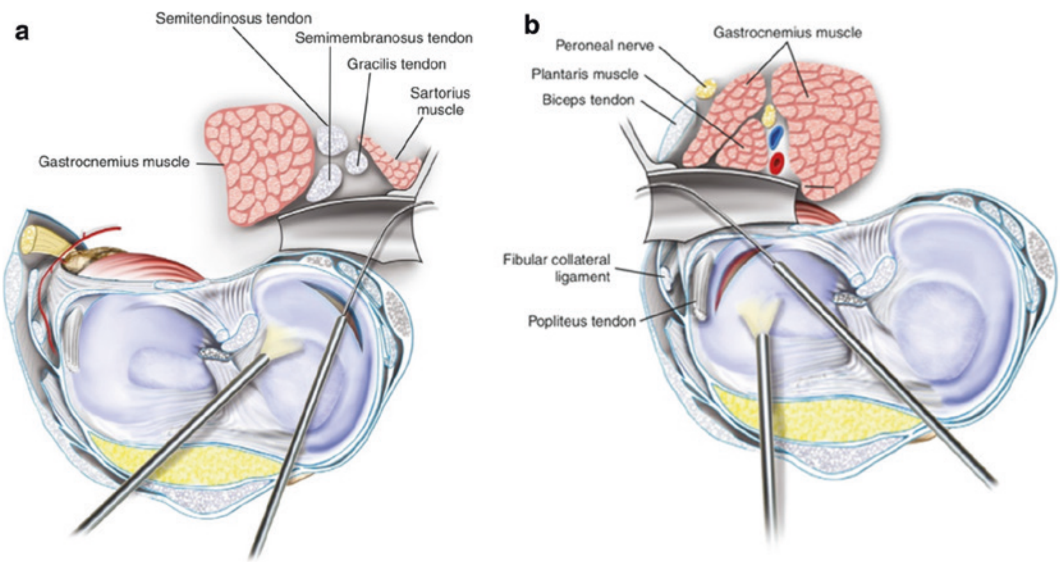

Fig. 7 **a** Posteromedial exposure, **b** Posterolateral exposure (Permission from Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd edition, 2017, Elsevier. Figure 23-7, Figure 23-9)

a torn meniscus 3 to 4 mm from the torn edge. The second assistant passes a 10-inch flexible needle through the cannula, aiming the needle in a slightly vertical direction so as to exit at or above the center of the torn edge. The first assistant catches the needle with the needle holder as

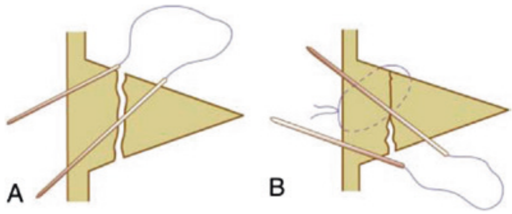

Fig. 8 Double-stacked vertical suture of inside-out repair. **A** The superior sutures are placed first to close the superior gap and to reduce the meniscus to its bed. **B** Then, the inferior suture is placed through the tear to close the inferior gap. (Permission from Noyes' knee disorders: surgery, rehabilitation, clinical outcomes. 2nd edition, 2017, Elsevier. Figure 23-10)

it exits through the capsule. The second needle is passed in the same manner to penetrate the outer side of a torn meniscus or directly meniscosynovial capsule, forming a vertical suture that provides better holding strength than a horizontal suture. The first assistant catches the double-armed needles and pulls the suture through. Both needles are cut, and the paired sutures are clamped together with a hemostat. To avoid the lift-up of the meniscus, the vertical divergent sutures are placed from both the superior and inferior surface of the meniscus alternatively every 3 to 5 mm (Fig. 8). If the tear involves mainly the middle third of the medial meniscus, the posteromedial exposure is not needed in most cases. Instead, a 1 to 2 cm incision is made directly over the needle tip coming from the joint, before passing the sutures through the skin to avoid cutting the suture during making an incision. When all sutures are passed out, they are tied over the capsule. If the capsule is not exposed completely, sutures may be tied over the subcutaneous tissue. This may lead to an insufficient reduction of the tear site. The surgeon closely observes the reduction of the meniscus body and closure of the tear site with passage and tying of the vertical divergent sutures. The articular cartilage is carefully protected to avoid damage during the procedures.

For lateral meniscus repairs, the surgeon should frequently check the direction of the suture needle to always ensure that it angles away from the peroneal nerve. The peroneal nerve moves more inferiorly with 90 degrees of knee flexion and less likely to be injured. If the tear involves the posterior horn of the lateral meniscus, the posterolateral corner is exposed. A 3 to 4 cm vertical skin incision is made just behind the lateral collateral ligament and dissected. The interval between the iliotibial band and the biceps femoris tendon is identified and dissected. The interval between the lateral gastrocnemius and the posterolateral capsule is opened bluntly, just proximal to the fibular head. A retractor is placed in this interval to push the neurovascular bundle posterolaterally (Fig. 7b). The retractor prevents the suture needles from potentially injuring the common peroneal nerve. Other technical details of the lateral meniscus repair are the same as the medial meniscus repair.

Outside-in Technique

With the outside-in technique, a suture is carried through a spinal needle that is inserted from outside of the joint to the meniscus. A specific advantage of this technique over the inside-out technique is to predictably avoid neurovascular injury without posteromedial or posterolateral exposure. A particular disadvantage of outside-in technique is the difficulty in repairing the tears located in the posterior horn. Therefore, the outside-in technique is especially useful for tears located in the anterior horn and the middle thirds of the meniscus. Modified outside-in methods have been evolved and introduced during the past years [6, 24, 42, 53, 72, 81].

Arthroscopic Outside-in Technique for a Longitudinal Tear of the Anterior Horn of the Meniscus

After diagnostic arthroscopy, an 18-gauge spinal needle is introduced from outside to identify the exact point of a meniscus tear. A small skin incision is made at the entry point of a spinal needle and the capsule is exposed after dissection. The first spinal needle is introduced from outside through the capsule to inside, penetrating the inner side of a torn meniscus in a vertical orientation from superior to inferior surface or vice versa (Fig. 9). The stylet is removed, and a suture (PDS 0) is passed through the spinal needle into the joint. The free end of the first suture inside the joint is taken out through an anteromedial or anterolateral portal and the first spinal needle is withdrawn. A second spinal needle is introduced through the same skin incision and entered through the outer side of a torn meniscus or just above or below the meniscus surface. The stylet is removed, and a shuttle-relay wire (or different colored second suture) is passed through the spinal needle into the joint. The free end of the shuttle-relay wire (or different colored second suture) is taken out through the same anterior portal and a second spinal needle is removed. A free end of the first suture is hooked to the shuttle-relay system (or tie 1st and 2nd suture together) and carried across the meniscus or capsule by pulling the shuttle relay (or a different colored second suture). Both free ends of the first suture on the outside are tied over the capsule. Same procedures are repeated to stabilize the meniscus tear firmly if needed. When the outside-in directed needle cannot be controlled adequately to place the sutures along with the exact point of the meniscus, the suture passer hook based modified techniques is helpful for better placement of vertical sutures at the exact point (Fig. 10) [4, 6]. Thompson et al. [81]

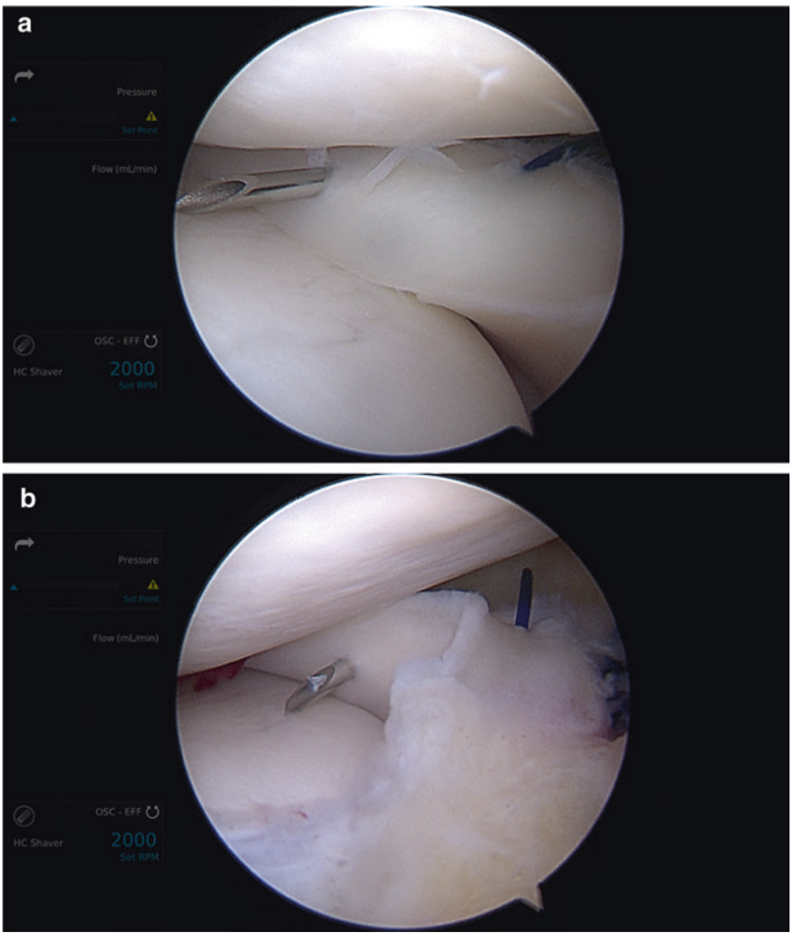

Fig. 9 **a** A spinal needle from the inferior to the superior surface of the medial meniscus, **b** a spinal needle from the superior to the inferior surface of the medial meniscus

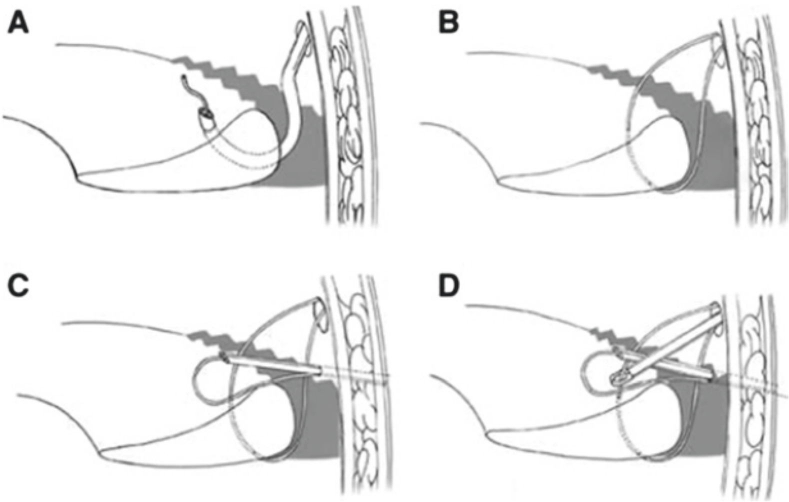

Fig. 10 Modified outside-in technique using a suture passer hook (Permission from Knee Surg Sports Traumatol Arthrosc (2006) 14:1288–1291, Fig 6)

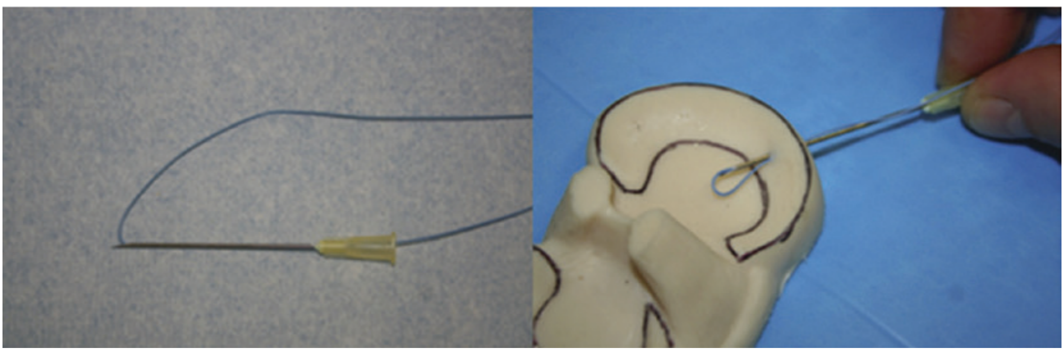

Fig. 11 A 21-gauge needle with a suture loop (Permission from Arthroscopy Techniques, Vol 3, No 2 (April), 2014: pp e233-e235, Fig 1)

also introduced the simple method of a suture retrieval when the special instruments are not available in the operating room (Fig. 11).

All Inside Technique

Neurovascular risks and additional posterior exposure with the inside-out repair technique and limited access to tears in the posterior third of the meniscus with the outside-in technique have developed fully arthroscopic all-inside repair techniques. The first-generation all-inside meniscal repair was a suture passer hook based repair through posteromedial or posterolateral portal, but their technical difficulties led to the development of all-inside meniscus devices [68, 82]. Advantages of all-inside meniscal repair devices include the technical ease of insertion, no need for secondary incisions, decreased operative times, and no need for the trained assistants. However, implant-related problems such as misfire, breakage, migration, and entrapment of the muscle, tendon, ligaments can occur during the procedures.

(1) All inside repair using a suture passer hook

A suture passer hook technique enables various suture orientation (vertical, horizontal, oblique, cross). So, it is useful for specific tears, including ramp lesions, radial tears, and posterior root tears. These suture passer hooks are curved, leftward or rightward, to a greater or lesser degree.

Arthroscopic Technique for a Longitudinal Tear at the Posterior Horn of the Medial Meniscus in Red-Red Zone

This technique is well described by Ahn et al. [5]. A 30° arthroscope is advanced from the anterolateral portal through an intercondylar notch between the medial femoral condyle and the posterior cruciate ligament to the posteromedial compartment. A standard posteromedial portal is made under direct arthroscopic visualization. Using a probe through a posteromedial portal, the extent of tear is assessed. A 30° arthroscope is switched to 70° arthroscope, which provides a wider view of posteromedial corner. A curved suture passer hook loaded with a PDS 0 (Ethicon, Somierville, NJ, USA) is inserted from the posteromedial portal. The tip of the suture passer hook first penetrates the capsular tissue from superior to inferior direction. After confirming the tip of the suture passer hook penetrating the full layer of the capsule, the tip of the suture passer hook enters the meniscus from inferior to superior surface (Fig. 12). The suture is then fed through the lumen of the cannulated hook and taken out through the same posteromedial portal using a suture retriever. Sliding or non-sliding knot tie is made and placed at the capsular side (capsular suture limb post). Additional sutures are placed by same procedures depending on the tear size. When it is difficult that a suture passer hook can be penetrated in a single step from the capsule to the meniscus, a two-step technique using a shuttle-relay method is recommended (Fig. 13). A first suture passer hook loaded with a PDS 0 penetrates from inferior surface to superior surface of the meniscus and a free end of the suture inside is retrieved through the posteromedial portal. A second suture passer hook loaded with a shuttle-relay wire (or a different colored second suture) then enter the capsule from superior to inferior direction. After a shuttle relay (or a different colored second suture) is fed through the lumen of the cannulated hook, a shuttle relay (or a different colored second suture) is retrieved through the same posteromedial portal. A free end of suture out of inferior surface of the meniscus is hooked to the relay system (or tie 1st and 2nd suture together) and carried across the capsule by pulling a shuttle relay (or a different colored second suture). The next procedures are the same as described above. A posteromedial cannula may be useful for managing sutures and tying knots to avoid soft tissue entrapment (Fig. 14) [2].

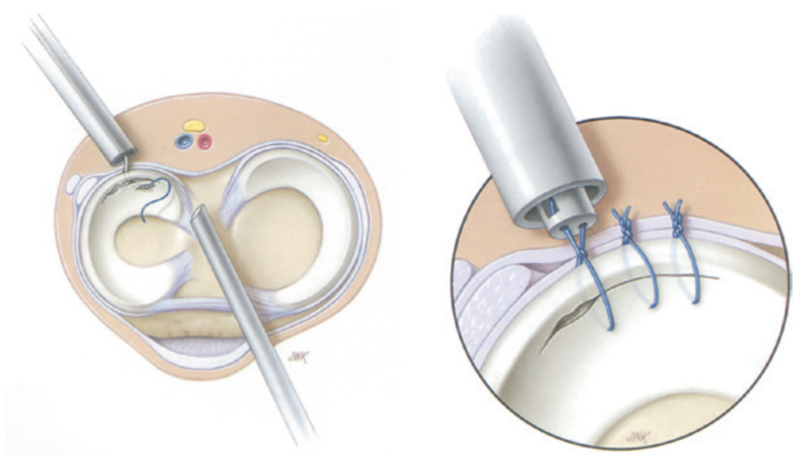

Fig. 12 All-inside meniscus repair using a suture passer hook through the posterolateral portal (Permission from Operative Techniques in Orthopaedcis, Vol 5, Issue 1 (January), 1995: pp 70–71, Fig. 4)

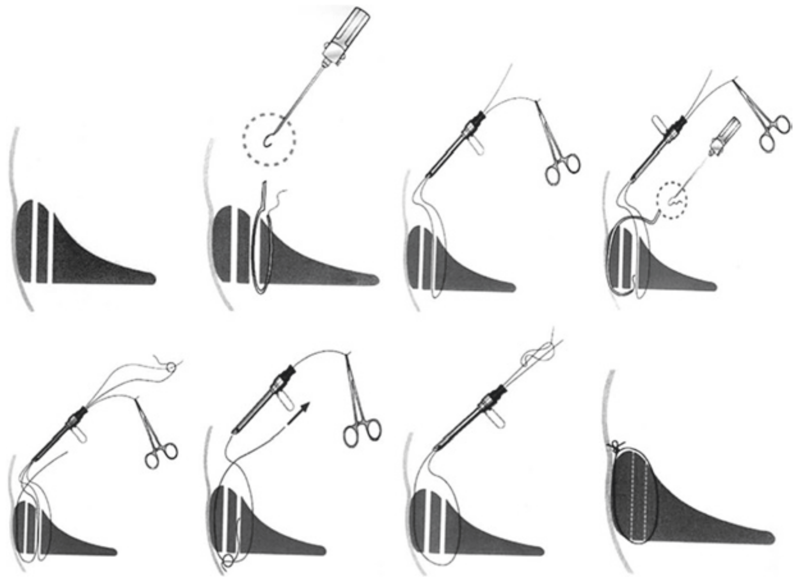

Fig. 13 All-inside meniscus repair using a shuttle relay method (Permission from Arthroscopy Vol 20, No 1 (January), 2004: pp 101–108, Fig. 2)

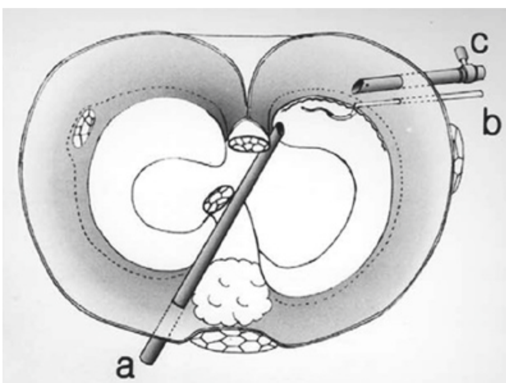

Fig. 14 All-inside meniscus repair using two posteromedial portals (Permission from Arthroscopy Vol 20, No 1 (January), 2004: pp101–108, Fig. 2)

(2) All inside meniscal repair devices

Currently, fourth-generation all-inside devices are available. They are flexible, and suture-based devices, and allow for variable compression and retensioning across the tear. The surgeon should know the specific features of each device including possible suture configuration, mode of deployment, location of knots, and tensioning method [82].

Arthroscopic All-Inside Technique Using the Fast-Fix 360® (Smith & Nephew, Andover, MA, USA) for a Longitudinal Tear of the Posterior Horn of the Lateral Meniscus (Fig. 15)

The Fast-Fix 360 meniscal repair system® (Smith &Nephew, Andover, MA, USA) consists of two implants (poly-etheretherketone, PEEK) attached with a pre-tied, self-sliding, non-absorbable 2-0 Ultrabraid™ suture. This device uses an active deployment system by a spring-assisted button with a 360° design that allows for deployment of any hand position. The active deployment devices have less misfires as compared with the passive deployment devices. The delivery needles are available in curved, straight, and reverse curved designs. After diagnostic arthroscopy and meniscal tear site preparation, the desired length limit of the delivery needle is determined using the meniscal depth probe. The tip of the probe is placed at the meniscosynovial junction and the width of the meniscus at the desired entry point for the delivery needle is measured. In the average size knee, a depth of 14–16 mm is usually

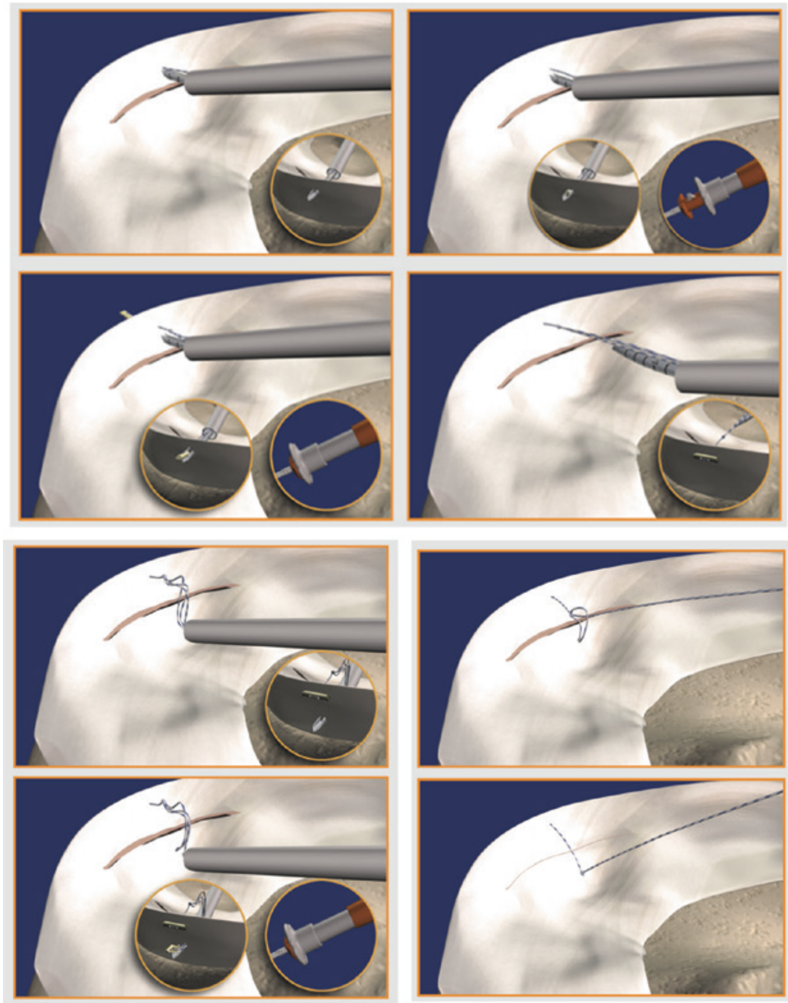

Fig. 15 All-inside meniscus repair using a Fast-Fix 360 (Permission from FAST-FIX 360 Meniscal Repair System. All-inside MeniscalRepair. Knee Series Technique Guide. Smith & Nephew)

adequate. The depth penetration limiter to the desired length by pressing the depth limiter button is adjusted. The slotted cannula can be used to help position the tip of the delivery needle at the desired location and avoid soft tissue entrapment. The delivery needle is introduced into the joint with the tip down against the slotted cannula and inserted into the capsular side of the meniscus (for a vertical mattress suture repair). The deployment slider is pushed forward all the way to deploy the first implant. Proper deployment is accompanied by a clicking sound. The delivery needle is withdrawn from the meniscus slowly, keeping the needle inside the joint. The delivery needle is positioned at least 5 mm from the tear site of the inner side meniscus and advanced until the depth penetration limiter contacts the surface of the meniscus. The deployment slider is forwarded all the way to deploy the second implant (should be accompanied by clicking sound). The delivery needle is withdrawn from the joint after deployment of the second implant. The free end of the suture is pulled to advance the sliding knot and reduce the meniscus. It is normal to encounter firm resistance as the knot is snugged down. It is important to pull the free end of the suture directly perpendicular to the tear site. The tension is applied slowly and steadily to the suture to cinch the knot down. The knot is further tightened to compress the tear site using a knot pusher/suture cutter and the suture is cut by pushing the trigger forward. Because of the high strength of the suture, using a small arthroscopic basket punch or scissors to cut the suture often results in the tail of the suture being frayed. The sutures can be placed alternatively on the inferior surface of the meniscus to reduce the puckering of the meniscus using the reverse curved delivery needle. If the remaining tissue of the capsular side meniscus is not sufficient for vertical mattress suture, sutures are placed in a horizontal mattress orientation. A minimum width of 8 mm between the two insertion points is recommended.

Repair for Specific Meniscus Tears

Meniscocapsular Junction Longitudinal Tear (Ramp Lesion)

The meniscus ramp lesion is a longitudinal tear at the meniscocapsular junction of the medial meniscus posterior horn and frequently occurs at the time of ACL injuries (Fig. 16) [20, 29]. A ramp lesion is reported to increase rotatory instability in ACL injured knees, and it is considered to be repaired [8, 18, 54, 62]. Several arthroscopic repair techniques for a ramp lesion have been introduced [19, 28, 34, 43, 57, 78, 79]. The author recommends to use a suture passer hook based all-inside repair through a posteromedial portal, which allows for placement of vertical sutures perpendicular to deep fibers of the meniscus. Technical details are the same as described above.

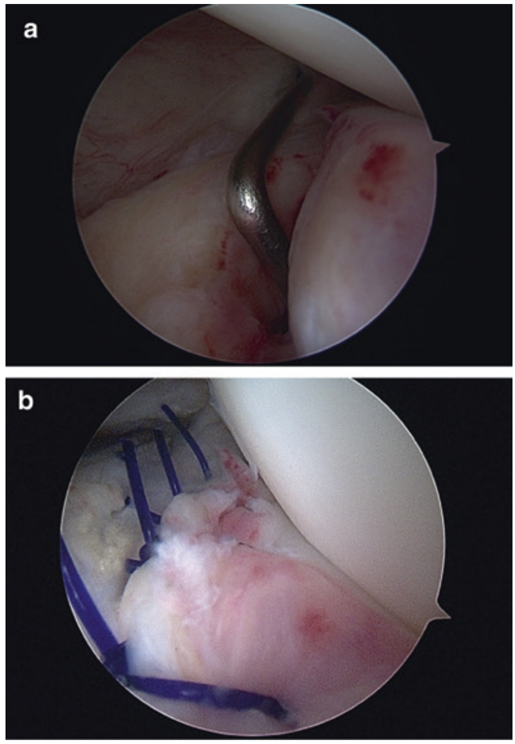

Fig. 16 **a** Acute ramp lesion of the medial meniscus combined with an ACL tear, **b** Four vertical sutures using all-inside repair through the posteromedial portal

Lateral Meniscus Popliteomeniscal Fascicles Tear

Three popliteomeniscal fascicles (anteroinferior, posterosuperior, posteroinferior) which combined with the popliteus tendon form a peripheral attachment to the lateral meniscus at the popliteal hiatus of the knee. Injuries to meniscotibial attachment including popliteomeniscal fascicles at the posterolateral aspect of the lateral meniscus lead to pain and hypermobile lateral meniscus [48]. Hypermobile lateral meniscus should be clinically suspected in patients with lateral or posterolateral knee pain and/or locking symptoms with squatting or figure four position. As MRI reveals no pathologic findings in most cases, it can be undiagnosed. At diagnostic arthroscopy, popliteomeniscal fascicles tears are suspected when there are enlarged popliteal hiatus with attenuation or tearing of the meniscus attachments, or subluxation of the posterior horn of the lateral meniscus by a probe or superior lift of the posterior horn of the lateral meniscus (Fig. 17). Arthroscopic viewing the lateral gutter through the anterolateral portal using 30° arthroscope and posterolateral compartment through the

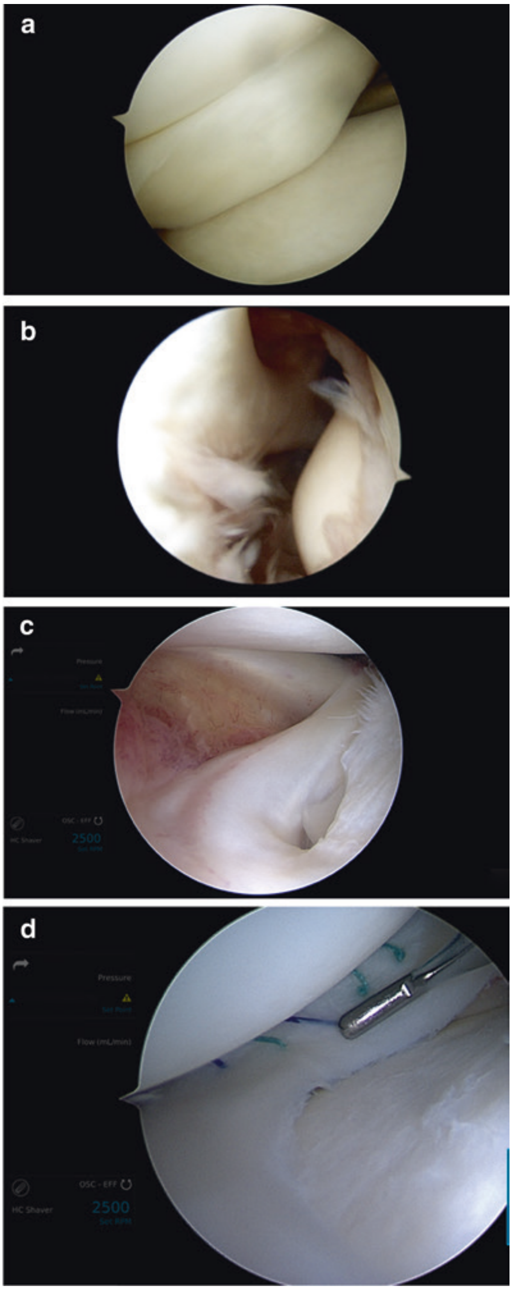

Fig. 17 **a** Subluxation of the lateral meniscus posterior horn, **b** enlarged popliteal hiatus with attenuation of the attachment of the lateral meniscus, **c** vertical longitudinal tear of the lateral meniscus around popliteal hiatus, **d** stable repair using inside-out and outside-in repair

anteromedial portal using 70° arthroscope can help assess the extent of peripheral attachment tear. Several authors have reported satisfactory outcomes following arthroscopic repair of peripheral attachment at the posterolateral aspect of the lateral meniscus [3, 40, 74, 84]. Multiple vertical sutures should be placed on either side of the popliteus tendon to reduce the lateral meniscus posterior horn to a normal tibial position and restore the meniscus attachments. The repair technique is the same manner as previously described lateral meniscus repair using inside-out or outside-in or all-inside techniques according to the surgeon's preference. In chronic cases, posterolateral synovial tissue is frequently found to be thin and redundant. The repair can be reinforced by placing sutures into meniscus tissue through the popliteus tendon to posterolateral capsule [3].

Radial Tear

A traumatic radial tear occurs more commonly at the midbody or near the posterior root of the lateral meniscus. Radial tears confined to the white-white or red-white zone may not be suitable for repair, because it is unlikely to heal due to poor blood supply. However, an acute complete radial tear extending to red-red zone or the meniscocapsular junction should be repaired, because it compromises the hoop tension of the meniscus. The goal of repair for a complete radial tear is to preserve meniscus function partially, because it is less likely to have successful healing of a tear in the white-white or red-white zone of the meniscus. Sutures can be placed on either side of the tear using an all-inside (suture hook, or all-inside devices), outside-in, or inside-out techniques according to the surgeon's preference (Fig. 18). Only two to four sutures can be placed for a radial tear, so the holding strength of the suture may be a concern. So, non-weight-bearing for 4 to 6 weeks is recommended to prevent disruption of the repair site. A number of techniques have been introduced recently to overcome the low holding strength [7, 17, 25, 51, 52, 58, 75] Wu et al. [87] reported satisfactory clinical outcomes at a mean 3.5 years follow-up. Fibrin clots also can be useful for enhancement of healing in the

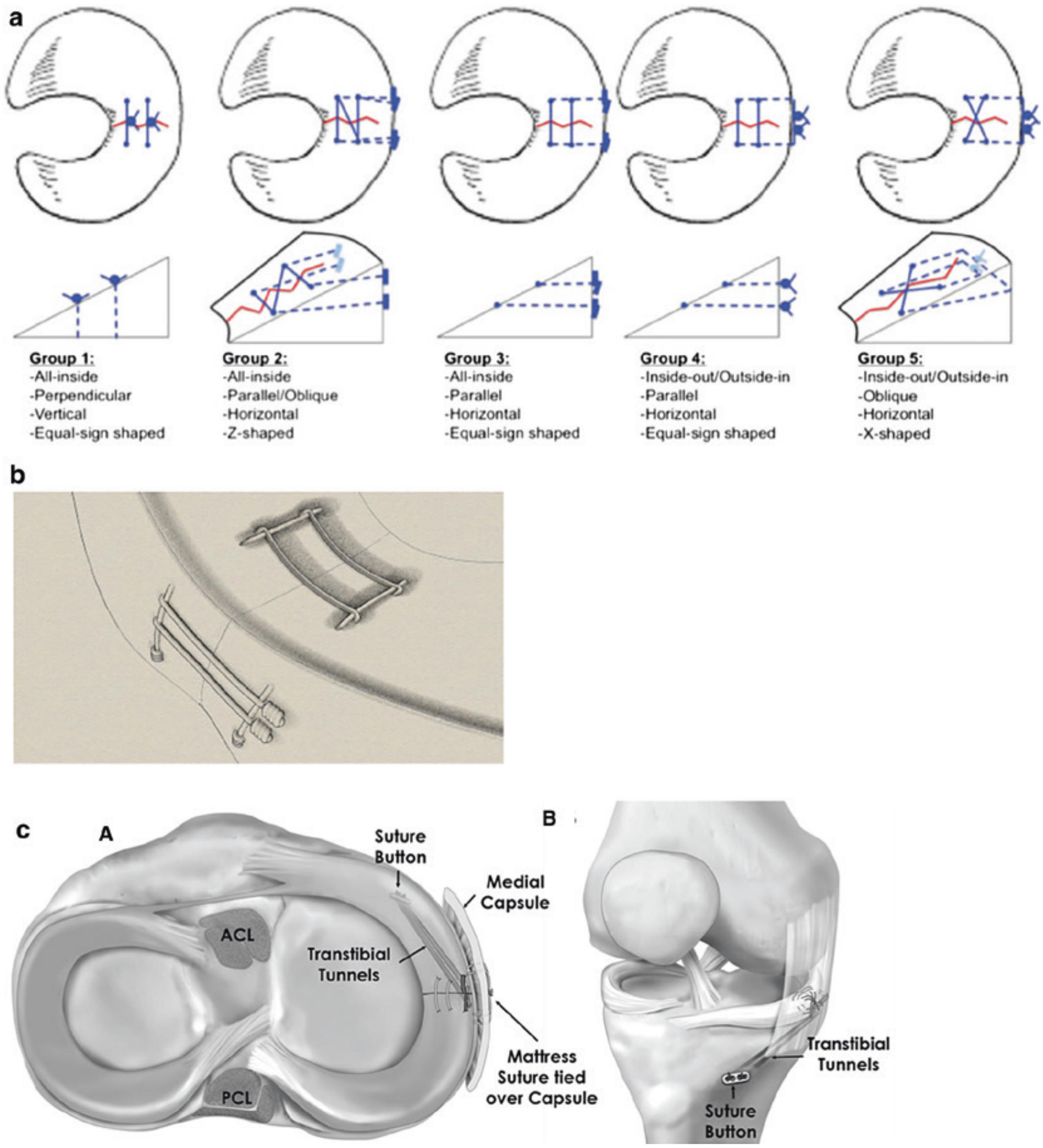

Fig. 18 **a** Various repair technique for a radial tear (Permission from J Knee Surg 2016;29:604–612, Fig. 2), **b** Rebar repair technique for a radial tear (Permission from Journal of Experimental Orthopaedics, 2019;6:38, Fig. 2), **c**criss-cross suture transtibial tunnel technique for a radial tear (Permission from Knee Surg Sports Traumatol Arthrosc (2015) 23:2750–2755, Fig. 3)

white-white or red-white zone of radial tears of the lateral meniscus [67]. Occasionally, the edges of the chronic radial tear are degenerative with a wide gap. Due to poor suture-holding capability, the meniscus tear edges may progress to separate, and poorly organized fibrous tissue replaces the gap during the healing process.

Horizontal Tear in Young Patients

Occasionally, a horizontal tear with good meniscus tissue quality is encountered in young patients. Traditionally, symptomatic horizontal tears that do not respond to nonoperative treatment are managed with meniscectomy.

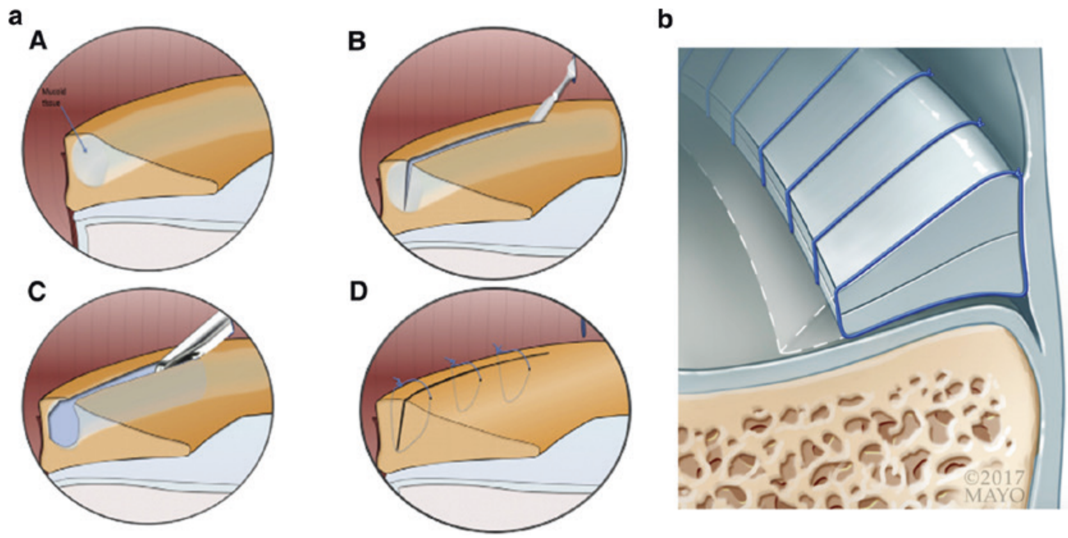

Fig. 19 **a** All inside repair for intrasubstance grade 2 lesion in the peripheral zone of the posterior horn of the medial meniscus (Permission from Arthroscopy Techniques, Vol 7, No 9 (September), 2018: pp e939-e943, Fig. 1), **b** circumferential compression stitch repair for a horizontal cleavage meniscus tear (Permission from Arthroscopy Techniques, Vol 6, No 4 (August), 2017: pp e1329-e1333, Fig. 5)

However, repair of horizontal meniscal tears is proven to be biomechanically advantageous to partial meniscectomy, [9] so repair can be considered in young patients. A number of repair techniques for horizontal tears have been introduced and vertical sutures with fibrin clots or platelet-rich plasm have shown successful healing and satisfactory clinical outcomes (Fig. 19) [14, 16, 46, 47, 66, 69, 80, 86]. However, a higher complication rate of meniscus repair for horizontal tears is also warranted compared to meniscectomy [71]. Intra-articular suture and knots may be abrasive to chondral surfaces when arthroscopic all-inside devices are used through anterior portals. For grade 2 horizontal tears (intrameniscal), arthroscopic or open repair is required through posteromedial approach [66, 80]. Detailed surgical techniques are referred to relevant references.

Root Tear

A root tear of the meniscus is discussed as a separate chapter elsewhere in this book.

Biologic Augmentation for Meniscus Healing

Biologic augmentation can enhance the repair process of meniscus tears that extend limited vascular zones of the meniscus [23, 33]. The abrasion at meniscosynovial junction or a microfracture (or drilling) in the intercondylar notch region is simply performed to produce bleeding that promotes adherence of fibrin clots at the repair site [27, 38, 59, 76, 77, 83]. An exogenous fibrin clot is also prepared and inserted at the repair site [21, 37, 47, 56, 67]. The exact mechanism of a fibrin clot is unknown, but it is expected that it may provide chemotactic and mitogenic stimuli. When anterior cruciate ligament reconstruction is performed concomitantly, successful healing of meniscus repair is expected without biologic augmentation. Case reports or small cases series have reported that platelet-rich plasma or stem cells application provides excellent healing, so they are a promising option for complex meniscus tears [13, 15, 39, 60, 65, 70]. However, clinical application is limited yet due to cost, time and the need of special equipment or facilities. Further clinical studies are required to determine whether they are superior to an exogenous fibrin or abrasion, microfracture.

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Discoid Lateral Meniscus

Jin Hwan Ahn and Sang Hak Lee

Abstract

The discoid lateral meniscus (DLM) is an infrequent anatomical variant, which usually affects the lateral compartment of the knee. Its estimated prevalence is low and higher rates have been observed in the Asian population. The identification of symptomatic DLM requires an appropriate level of clinical suspicion based upon the patient's medical history and symptoms, the judicious use of imaging studies (including plain films and magnetic resonance imaging (MRI)), and diagnostic arthroscopy. It is the authors' experience that a high frequency of bilaterality occurs with a high prevalence of peripheral tears that require repair. The MRI classification can aid surgeons in predicting the occurrence of peripheral tears and degree of instability as well as plan the treatment method preoperatively. Current treatment recommendations favor meniscal reshaping through partial meniscectomy with or without repair. However, arthroscopic reshaping can be challenging to an inexperienced surgeon because visualization within the lateral joint space may be limited by a thickened meniscus and the small size of the pediatric knee. It is believed that the described technical guide to arthroscopic partial meniscectomy in conjunction with the meniscal repair of the peripheral tear is an effective method.

Keywords

Discoid lateral meniscus · Meniscal reshaping · Meniscus repair · Meniscectomy

Incidence and Bilaterality

The discoid meniscus, although a relatively rare congenital anatomical abnormality of the lateral meniscus, is the most common anatomic meniscal variant. First described by Young in 1889 [45], its incidence has been estimated to be around 5% in the general population, ranging from 0.4 to 16.6% in different series in the literature with a higher prevalence among Asian populations [18, 21, 22, 28, 35]. Most discoid menisci are located on the lateral side; however, rare descriptions of medial discoid menisci have been sporadically reported in the literature [19, 40, 41].

J. H. Ahn
Department of Orthopaedic Surgery, Saeum Hospital, 8, Siheung-Daero 139-Gil, Geumcheon-Gu, Seoul, Republic of Korea
e-mail: jha3535@naver.com

S. H. Lee (✉)
Department of Orthopaedic Surgery, Kyung Hee University Hospital at Gangdong, 892 Dongnam-Ro, Gangdong-Gu, Seoul, Republic of Korea
e-mail: sangdory@hanmail.net

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The incidence of bilateral discoid lateral menisci (DLM) is estimated to be as high as 20%; however, the true incidence of bilateral DLM may be underestimated because the contralateral knees in most patients are asymptomatic. However, 1 prospective study involving contralateral magnetic resonance imaging (MRI) evaluation of patients with unilateral symptomatic DLM showed a discoid meniscus in 97% of patients, revealing the contralateral side to have an identical discoid shape in 88% of cases [5]. Recently, additional studies have reported the prevalence of bilateral DLM to be from 73% to 85% according to bilateral arthroscopic examination or MRI evaluation [13, 16, 24]. Furthermore, these reports have demonstrated associated meniscus tears on the contralateral side at a rate of 4% to 33% in patients with symptomatic, unilateral surgical DLM (Fig. 1). A few studies have identified potential factors that may predict the survivorship of the contralateral meniscus in patients with DLM, however. The recent study demonstrated that older, symptomatic DLM patients with more degenerative changes may be at risk for a similar condition in the contralateral knee [24]. Moreover, mid- to long-term follow-up studies revealed that 17% to 23% of cases later required surgery in the contralateral knee. Sasho et al. [38] reported that the risk of needing surgical treatment on the contralateral knee was high in the first 2 years following the initial surgery. This finding could indicate a high vulnerability of the contralateral knee during the early rehabilitation

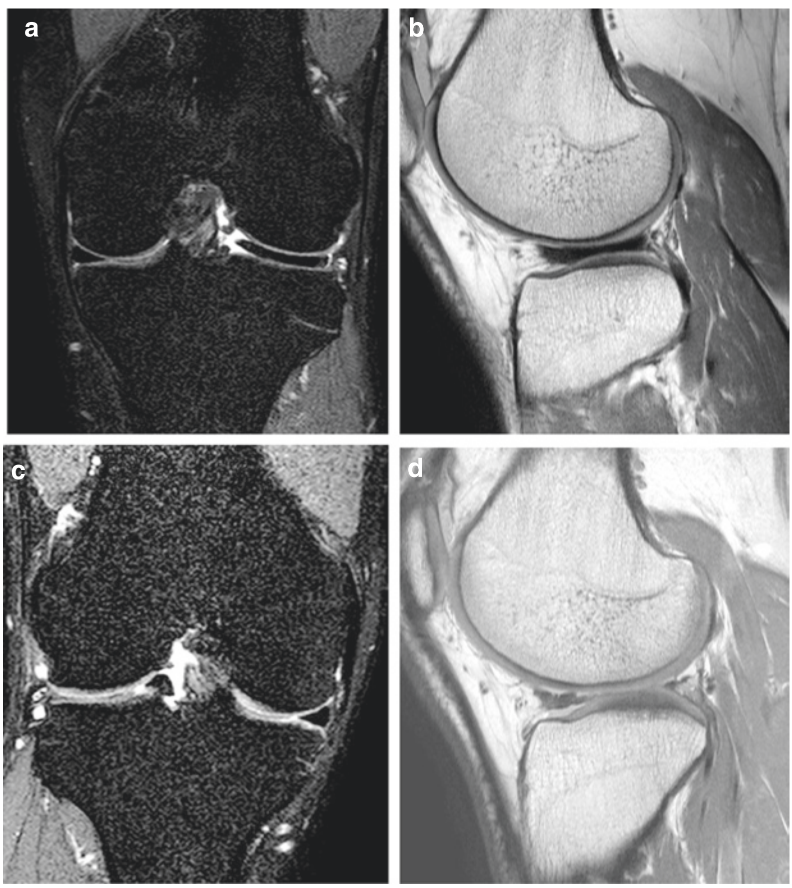

Fig. 1 **a** Coronal and **b** sagittal images show only complete type discoid lateral meniscus without shifting. **c** Coronal and **d** sagittal images show anterior and central shift of the discoid lateral meniscus in the contralateral side

phase [30]. And Kim et al. [24] demonstrated the number of characteristic X-ray findings in the contralateral knee is a significant predictive factor for contralateral DLM type and/or tear. Long-term follow-up with MRI screening for asymptomatic contralateral knees is necessary to determine the fate of the contralateral knee.

Classification and Diagnosis

Historically, pathogenesis theories ranged from an embryologic arrest in development resulting in incomplete resorption of the central meniscus, to theories regarding this anomaly as a congenital anatomic variant, which is currently accepted. Watanabe et al. presented in 1969 the most commonly used classification system for lateral discoid meniscus, describing three types based on arthroscopic appearance [44]: Type I, the most common type in most series, is a complete discoid meniscus which covers the entire tibial plateau with intact peripheral attachments. Type II is an incomplete discoid meniscus, covering a variable percentage of the tibial plateau, with intact attachments. Type III, the least common, is an unstable discoid meniscus, also known as the Wrisberg ligament type, as it is characterized by absent normal posterior attachments with only the meniscofemoral ligament of Wrisberg providing posterior stabilization, resulting in significant meniscal mobility which often manifests clinically. Unstable DLM are commonly symptomatic and require surgical treatment.

Most of the discoid menisci are either asymptomatic or incidental arthroscopic findings [12, 32]. However, in symptomatic cases, the symptoms are highly variable depending on the type of DLM, its location, the presence or not of a tear, and rim stability [6, 28] (Fig. 2). The onset of symptoms might not be preceded by a clear trauma and is present since childhood in some cases. Conversely, symptoms appear later in adulthood in a number of knees with a DLM. In general, discoid menisci with normal peripheral attachments tend to be asymptomatic, and this is the case in many children, therefore requiring no treatment. However, with tissue variability and abnormal knee kinematics with high shear stresses, discoid menisci are at an increased risk for the development of tears, which are often revealed clinically during childhood. Patients often present with mild, vague lateral joint line pain and swelling with or without an inciting event. Mechanical symptoms are present in displaced tears or an unstable variant, manifesting as palpable or audible "clicking," "snapping," or "popping" or even an extension block. Ahn et al. [9] reported that the two most frequent preoperative clinical manifestations were pain and extension block with 39 lateral DM in children. They also suggested that the extension block was significantly more common in patients with

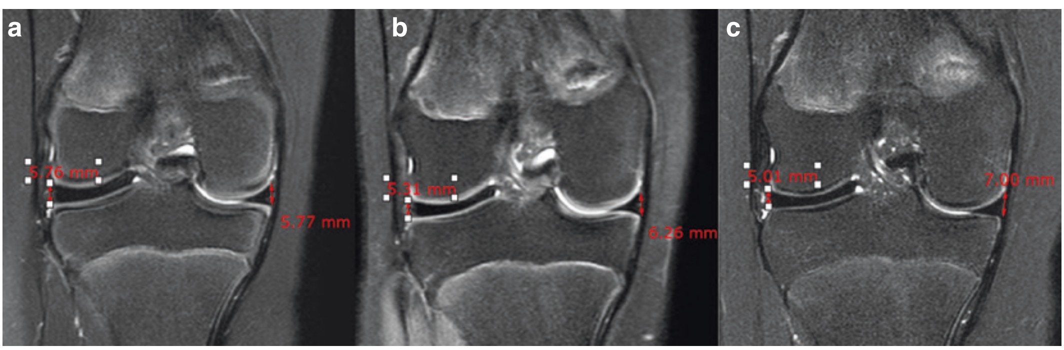

Fig. 2 **a** Coronal image of a-9-year-old girl shows discoid lateral meniscus without a definite tear. Conservative treatment can be maintained. **b** After 2 years, there is no definite tear, and thickness of discoid lateral meniscus is not thicker than that of medial meniscus. **c** After 3 years, asymptomatic discoid lateral meniscus without tear can be continued with no surgical treatment

the thickened anterior type than in the thickened posterior type.

Radiographs are a mandatory part of the evaluation, and may reveal widening of the lateral joint space, lateral femoral condyle flattening, concavity of the tibial plateau, meniscal calcification, and tibial spine hypoplasia. A simple radiological study can still provide some useful information [26]. Choi et al. [14] quantitatively compared radiographic findings of symptomatic DLM in children with those of matched controls. Significant differences in the mean height of the lateral tibial spine, the lateral joint space distance, fibular head height, and obliquity of the lateral tibial plateau between the two groups were observed. Those authors suggested these findings would be helpful as a screening tool for DLM in children (Fig. 3). Concomitant osteochondritis dissecans of the lateral femoral condyle has also been reported and should be looked for [27, 31] (Fig. 4).

MRI, aiding not only in diagnosis but also in decision-making and preoperative planning, demonstrates irregular continuity of the anterior

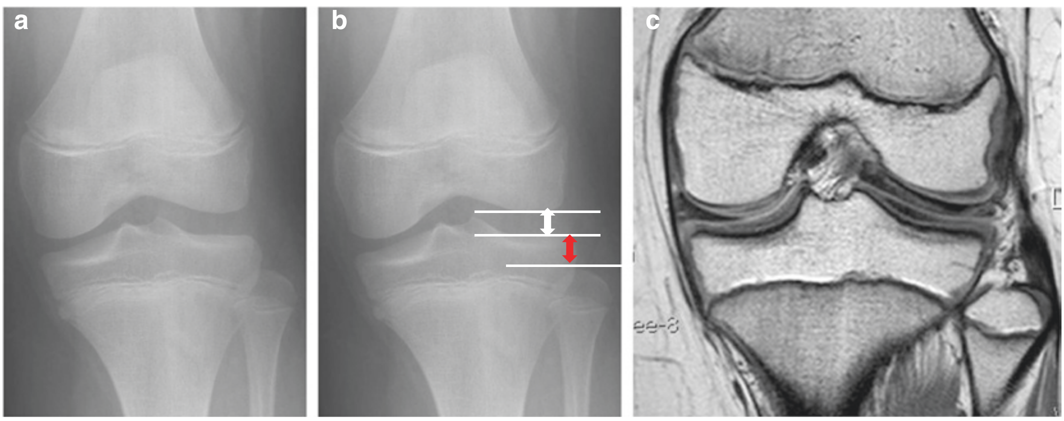

Fig. 3 **a** Anteroposterior view seems to be normal radiograph of a 13-year-old boy. **b** Anteroposterior view shows widened lateral joint space (8.3 mm) and elevated fibular head (12.1 mm). **c** Coronal MR image shows discoid lateral meniscus of complete type

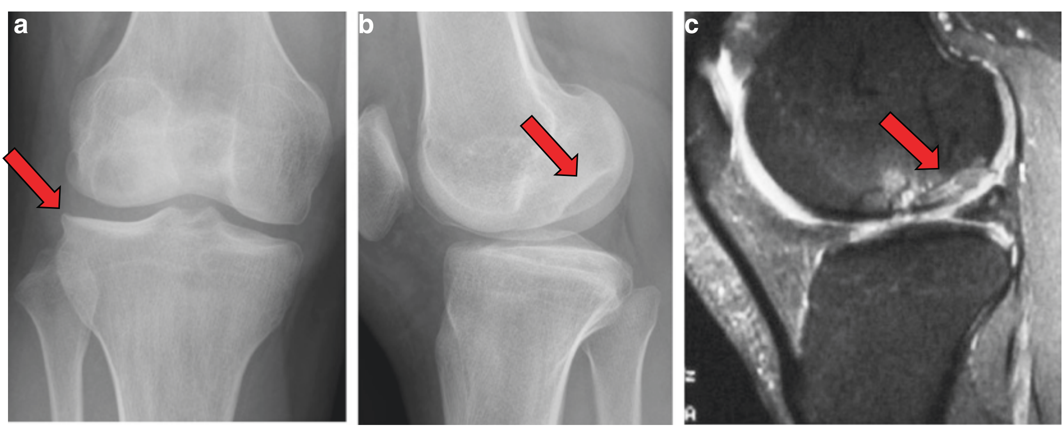

Fig. 4 **a** Anteroposterior view of an 18-year-old boy shows lateral marginal osteophyte (arrow) and **b** lateral view shows osteochondritis dissecans of the lateral femoral condyle (arrow). **c** Sagittal MR image shows discoid lateral meniscus of posterior shift type with concomitant osteochondritis dissecans (arrow)

and posterior horns of the lateral meniscus (absent 'bow-tie') in three or more consecutive 5-mm cuts. Intra-substance tears and displaced flaps are often well visualized; however, unstable type III variants are more difficult to detect on MRI [27, 39]. Choi et al. [15] have recently published a diagnostic criterion to distinguish between complete and incomplete lateral DM based on MR images. In order to provide more information to surgeons in choosing the appropriate treatment methods, Ahn et al. [7] further analyzed the sensitivity, specificity, and accuracy of a shift in preoperative MRI depending on the existence of peripheral tear when corroborated with arthroscopy. However, this MRI classification is not sufficient, and other aspects, such as a careful history and physical examination are always essential. A DLM with a peripheral tear might appear as having no shift if it is reduced at the time the MRI is performed. It is, therefore, still important to correlate/incorporate clinical findings with the imaging findings. If a loud click is present in cases of DLM, a peripheral tear must be suspected and should be addressed by careful arthroscopic examination. In addition, DLMs frequently have horizontal and inferior tears that are not easily identified with arthroscopy, and can be often missed without suspecting these possibilities and without a thorough arthroscopic examination. MRI can provide valuable information about the existence of horizontal tears which cannot be obtained from arthroscopy. Careful arthroscopic evaluation should be made because these types of tears are commonly associated with all types of DLM. Also, a peripheral longitudinal tear starts from the popliteal hiatus and extends to the posterior or anterior horn.

Surgical Treatment

In these symptomatic cases, surgery is indicated with the goal of symptom relief and meniscal tissue preservation to obtain functionality as well as avoid early degeneration [6, 28]. In the past, total meniscectomy was widely acceptable for the treatment of discoid meniscus [34, 43]. However, later reports showed the advantages of arthroscopic saucerization. Although it is no longer considered an appropriate treatment choice, it is still performed in situations where meniscal preservation is not feasible. The available evidence reveals fair to poor long-term clinical outcomes in patients after total meniscectomy, with radiographic follow-up has demonstrated high rates of degenerative changes and arthrosis of the involved compartment. These patients should be closely followed for early symptomatic appearance as the option of meniscal transplantation might be considered in cases.

Currently, treatment guidelines are based on the type of meniscal variant, its stability, presence of a tear, tear type, symptom severity and duration, and the patient's age. Treatment options include observation, partial meniscectomy or saucerization, with or without repair or reattachment of an unstable peripheral rim, and total meniscectomy. Asymptomatic discoid menisci are often identified incidentally (during radiographic or MRI evaluation) and are usually addressed with observation alone. Symptomatic stable DLM are usually treated with arthroscopic "saucerization" [1, 20, 42]. The goal in this procedure is to retain a peripheral rim (ideally, a residual rim width of 6 to 8 mm) resembling a normal meniscus, in order to more closely reproduce meniscal anatomy and function and to avoid re-tear. Recently, Kim et al. [23] analyzed the postoperative size of DLM using MRI after partial meniscectomy relative to the size of medial meniscus midbody. This study resulted that the mean width of the remaining DLM after surgery was comparable to the MM width when a partial meniscectomy with or without repair was performed in reference to the width of the MM. So this novel surgical reference, size of midbody of medial meniscus, could be appropriate for sufficiently preserving the DLM for partial meniscectomy in symptomatic complete DLM.

If significant instability persists after saucerization, a repair is required to stabilize the unstable residual portion to the capsule. DLM with an unstable rim is ideally treated with combined saucerization and repair of the peripheral rim to stabilize the reshaped meniscus to the capsule. Addressing these variants commonly requires multiple sutures as they tend to be highly unstable. Various meniscal repair techniques can be utilized for this purpose, such as the 'inside-out' technique, the 'outside-in' technique, and the 'all inside' technique. Indications for technique choice are based on repair location, tear type, and the surgeon's preference. Anterior rim instability is more easily addressed with an 'outside-in' technique.

Diagnostic Arthroscopic Examination

A standard arthroscopic diagnostic arthroscopic examination is initially performed under general anesthesia, using a 4.0 mm arthroscope [2, 6]. The 2.7 mm arthroscope is rarely used only if the joint cavity is insufficient to allow diagnosis with a standard arthroscope. The routine diagnostic examination is performed using the standard anterolateral viewing portal. For simplified evaluations and to access the anterolateral compartment, the arthroscope is moved to the anteromedial portal, enabling a more thorough inspection as thick meniscal tissue may disturb optimal visualization of the DLM. Careful probing is performed to identify discoid meniscus type, tear shape, and to evaluate the stability of the peripheral rim. In cases of DLM, it is often difficult to visualize peripheral longitudinal tears at the posterior horn through the standard anterior portals due to the thick meniscal tissue. Peripheral rim tears at the posterior horn of the lateral meniscus could be examined with the arthroscope inserted through the anteromedial portal and passed through the intercondylar notch between the anterior cruciate ligament and the lateral femoral condyle. A 70º arthroscope could be used for better visualization. Also, switching the scope to a posterolateral portal enables peripheral rim tears of the posterior horn to be positively verified.

Partial Central Meniscectomy

Partial central meniscectomy is performed in a "1-piece" fashion or "piecemeal technique." The goal of partial central meniscectomy is to remove the central portion of the thickened meniscus and the torn unstable portion and to leave a stable rim of more than 6 mm from the peripheral capsular attachment. In children, an inspection of the medial meniscus could be helpful to determine the size of the remaining peripheral rim after saucerization (Fig. 5). Sometimes the meniscal morphology could not be properly verified owing to peripheral rim instability, and a single stitch suture is then performed to reduce the meniscus prior to the central partial meniscectomy. Using Iris scissors through the anterolateral portal, the anterior and mid-portion of the discoid meniscus is cut leaving a margin of more than 6 mm from the periphery of the meniscus and the posterior portion of the discoid meniscus is cut to similar margins from the periphery of the meniscus using arthroscopic scissors or basket forceps through the anterolateral portal (Fig. 6). Iris scissors are useful to cut the anterior or mid-portion of the discoid meniscus and trim the thickened portion of the discoid meniscus. After extracting the central portion of the discoid meniscus in one piece, the inner rim of meniscus is smoothed with a basket forceps or a motorized shaver. For horizontal tears, since the lower leaf is usually unstable, only the lower leaf is resected. Once the desired amount of meniscal tissue has been removed, the thickness of the inner edge is much greater than that after routine partial meniscus excision. Additional remaining thickened portions of the meniscus are also trimmed using a basket forceps or iris scissors, to avoid potential extension block. In order to remove a flap tear of the inferior rim of the anterior horn, the use of a basket forceps or a shaver through the submeniscal portal could be useful.

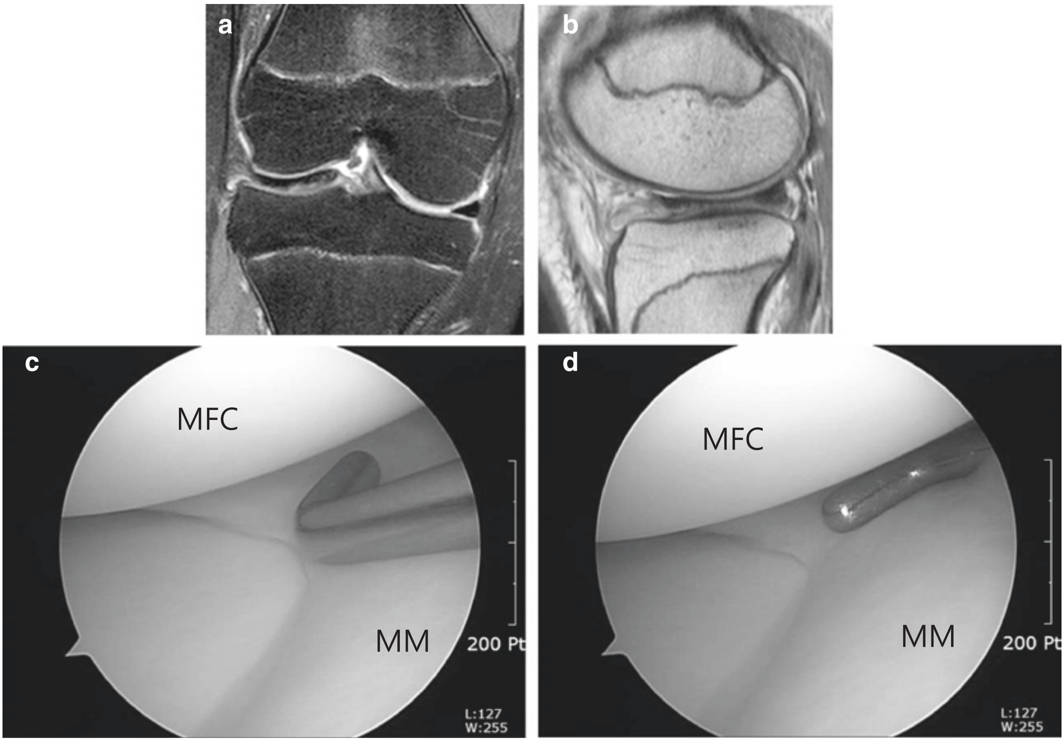

Fig. 5 **a** Coronal and **b** sagittal images of a 13-year-old girl show complete type discoid lateral meniscus with horizontal tear. Posterocentral shift type of the discoid lateral meniscus in the right knee. **c**, **d** Arthroscopic findings show the width of the medial meniscus (MM) that can be measured with a probe. (MFC medial femoral condyle)

Meniscus Suture Repair for Peripheral Tears

Once the central portion of the meniscus has been removed, the remaining peripheral rim must be carefully probed to ensure that there are no additional tears and that the rim is balanced and stable. At this point, when the peripheral rim tear of the DLM is reducible with a probe, the suture repair is performed. In cases where posterolateral corner loss of the DLM is too extensive and irreducible with a probe, subtotal or total meniscectomy should be considered. The number of sutures needed for repair could be used as a measure for tear size as the actual measurements are usually difficult to perform. Although not optimal, this provides a rough estimate of tear size, as stitches are placed at roughly 3–4 mm intervals.

Our preferred repair technique is performed using absorbable sutures (No. 0 PDS: Ethicon, Sommerville, NJ, USA) after debridement of the tear sites using a motorized shaver. In order to suture tears from the anterior horn to the posterolateral corner, a modified outside-in technique is preferred using a suture hook (Linvatec, Largo, FL) with a straight neck and a spinal needle preloaded with a No. 0 nylon, enabling to pull out the PDS [8]. This technique is performed using a small posterolateral incision for easy retrieval and suture tying. For suturing tears in the posterior horn, a modified all-inside technique is preferred using a suture hook with a 45-degree curved neck through a single posterolateral portal. If a tear could not be repaired due to posterolateral corner loss of more than 1 cm, an arthroscopic subtotal meniscectomy is performed.

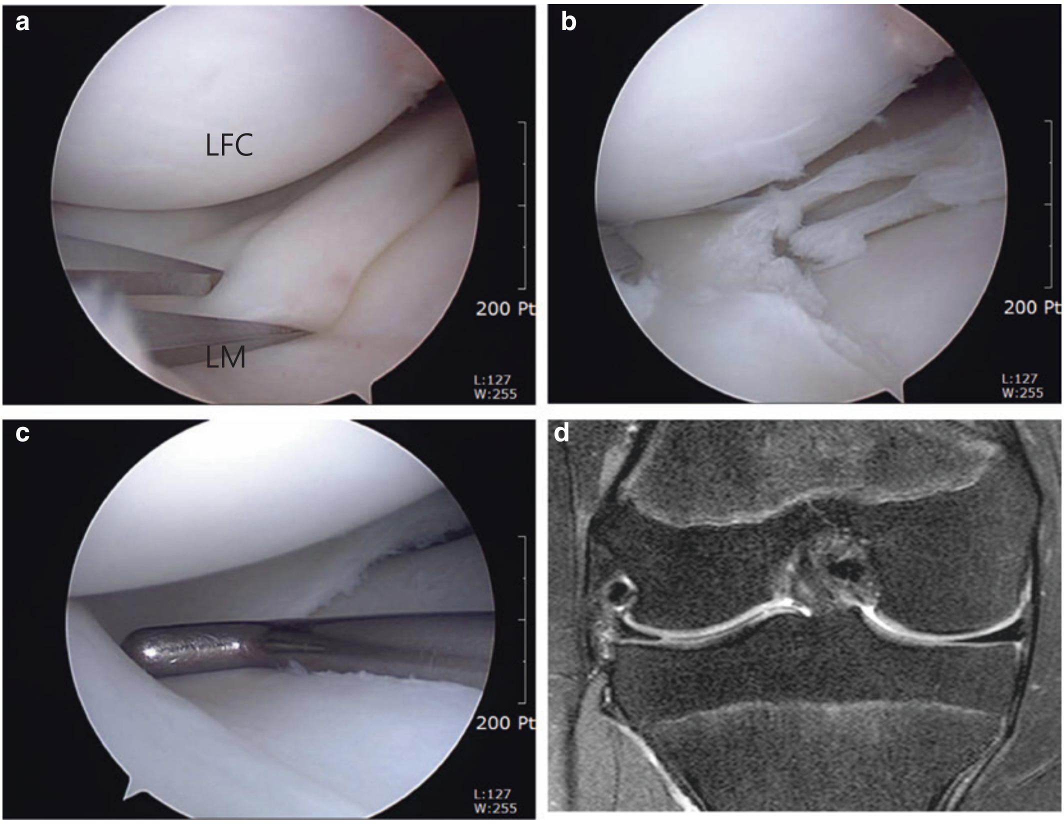

Fig. 6 Arthroscopic findings show **a** the discoid meniscus was cut with an iris scissors through the anterolateral portal a meniscocapsular junction tear between the lateral meniscus anterior horn and the joint capsule. **b** Horizontal tear of discoid lateral meniscus can be seen. **c** Peripheral rim of discoid lateral meniscus was preserved the same size with midbody of medial meniscus. **d** coronal and sagittal magnetic resonance imaging shows complete healing of the tear site with a lateral meniscus of normal shape at 6 months' follow-up. (LFC lateral femoral condyle)

The Modified Outside-In Technique for Tears from the Anterior Horn to the Posterolateral Corner

The modified outside-in suture technique is performed using a spinal needle which is used in the standard outside-in suture technique [10] and a suture hook (Linvatec TM; Largo, FL, USA) which is generally used for the all-inside suture technique. First, an arthroscope is introduced through the anteromedial portal, and a semilunar shaped straight suture hook (LinvatecTM) is inserted through the anterolateral portal. First, the meniscus is pierced from the lower surface to the upper surface by orienting the suture hook in a vertical direction (Fig. 7). Next, the No. 0 PDS (Ethicon, Sommerville, NJ, USA) suture material is advanced through the cannulated suture hook. After withdrawing the suture hook from the joint, the suture ends are retrieved through the ipsilateral portal using a suture retriever.

Under the arthroscopic vision, a spinal needle with a preloaded MAXON 2-0 is inserted above the meniscus in order to pull out the previously inserted PDS through the torn meniscus. The MAXON 2-0 loop is then manipulated so that it is oriented in front of the No. 0 PDS. The No. 0 PDS is retrieved through the MAXON loop with a suture retriever and the suture ends are pulled outside the capsule by pulling the MAXON loop outward. An additional spinal needle, preloaded

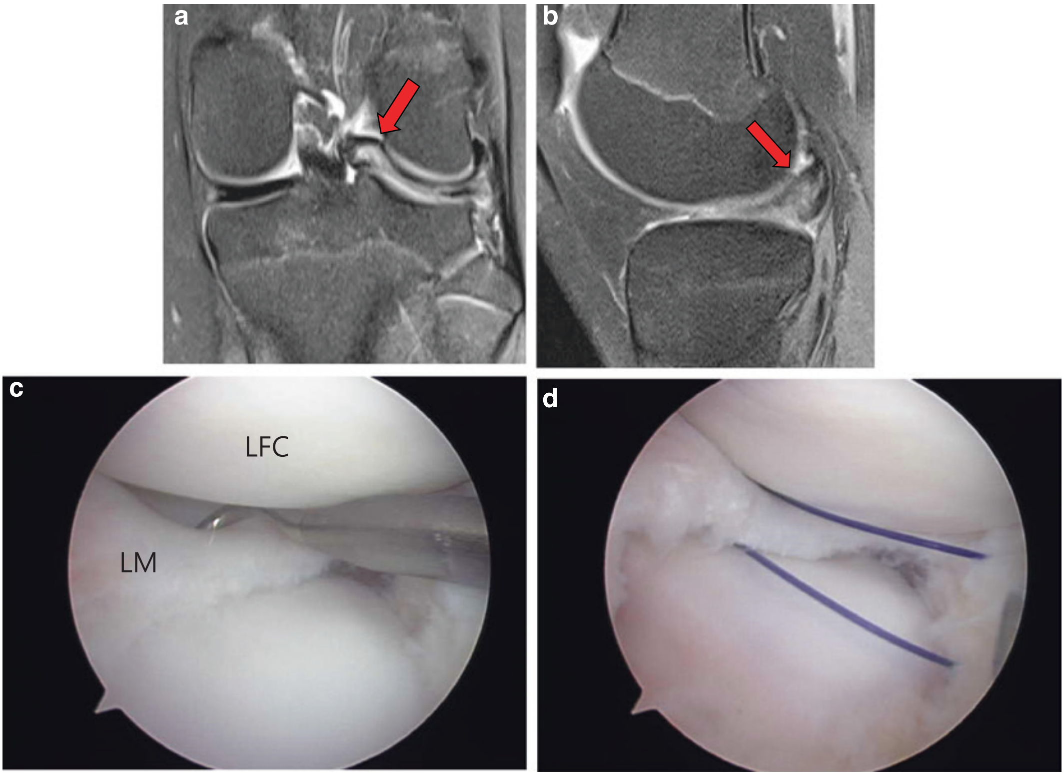

Fig. 7 **a** Coronal and **b** sagittal images of a 15-year-old girl show posterocentral shift type of the discoid lateral meniscus (arrows) in left knee. **c**, **d** Arthroscopic photograph showing a meniscocapsular junction tear between the lateral meniscus anterior horn and the joint capsule. Suture hook inserted into the anterolateral portal penetrates the lateral meniscus anterior horn (LM). Both suture ends are retrieved through the MAXON loop with a suture retriever. (LFC lateral femoral condyle)

with a MAXON 2-0, is reinserted—this time below the meniscus—in order to pull out the other end of the previously passed PDS through the torn meniscus. The loop is again adjusted to be positioned in front of the PDS suture end below the meniscus. This end is now retrieved through the MAXON loop and is then pulled outside the capsule by pulling the MAXON loop outward. The torn meniscus is reduced by pulling both ends of the No. 0 PDS, which now holds the circumferential fibers of the meniscus.

A 1 to 2 cm sized skin incision is made close to the two ends of the PDS suture. Using a curved haemostat, the area is dissected down to the level of the retinaculum. The two PDS suture ends are then retrieved through the incision confirming there is no soft tissue interposed between the free ends of the PDS, apart from the retinaculum. After reduction of the meniscus, both suture ends are tied with optimal tension, achieved by manipulating a probe inserted through the anterolateral portal. After placement of the sutures, the gap between the meniscus and the joint capsule is closed (Fig. 8).

The Modified All-Inside Technique for Posterior Horn Tears

In DLM, it is very difficult to find the peripheral longitudinal tear at the posterior horn through standard anterior portals due to thick meniscal tissue that often obstructs optimal visualization and inspection of this portion of the meniscus [3, 4] (Fig. 9). The PL compartment can be approached by passing a 30° arthroscope

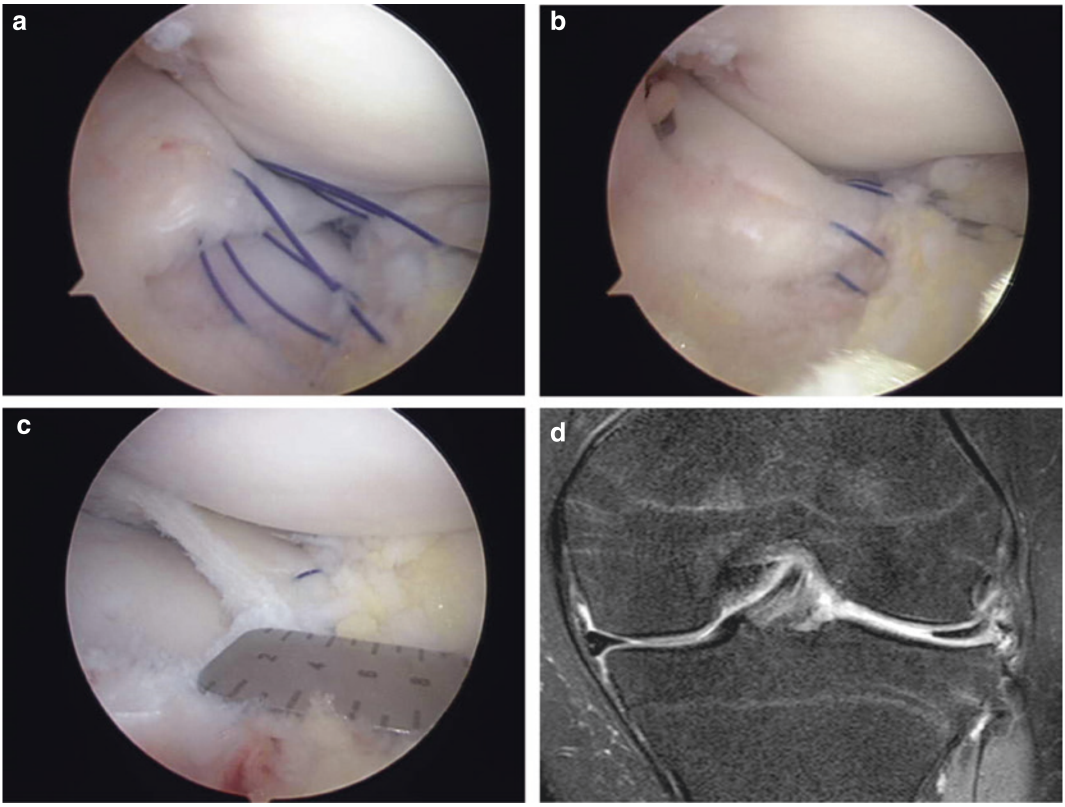

Fig. 8 **a**, **b** The torn meniscus is reduced by pulling 3 stitches of the No. 0 PDS, which now holds the circumferential fibers of the meniscus. **c** After partial meniscectomy with repair, peripheral rim of lateral meniscus was preserved with 9-10 mm that is the similar size of the midbody of medial meniscus. **d** coronal magnetic resonance imaging shows complete healing of the tear site with a lateral meniscus of normal shape at 6 months' follow-up

between the anterior cruciate ligament and the lateral femoral condyle. Once a peripheral longitudinal tear of the lateral meniscus posterior horn (LMPH) is identified via standard diagnostic arthroscopy, a 70° arthroscope can be used for better visualization. Various anatomic structures in the PL compartment, such as the LMPH, the PL capsules, and the lateral femoral condyle are examined using a 30° arthroscope inserted at the anteromedial portal and passed through the intercondylar notch. While keeping the knee flexed at 90° for maximal joint distension and to avoid neurovascular injury, a 16-gauge spinal needle is inserted at the posterolateral (PL) corner using a trans-illumination technique and a PL portal is established, without the use of a cannula. A probe is inserted to examine the extent, degree, and shape of the peripheral tear at the LMPH. The arthroscope is switched to the PL portal by use of a switching stick to examine the PL compartment and the torn LMPH from a different view.

In more anatomically confined PL compartments, it is often difficult to manipulate the instruments sufficiently. The arthroscopic all-inside suture of LMPH tear through a single PL portal was developed to address such limitations. Our suturing technique allows greater freedom in suture hook maneuvering by creating a single PL portal without using a cannula. This technique allows excellent visualization of the PL compartment, anatomic coaptation of the torn meniscus, and strong efficient knot tying, while avoiding inadvertent injury to the remnant meniscus and the articular cartilage. We recommend this technique for suture placement in peripheral longitudinal tear of the LMPH.

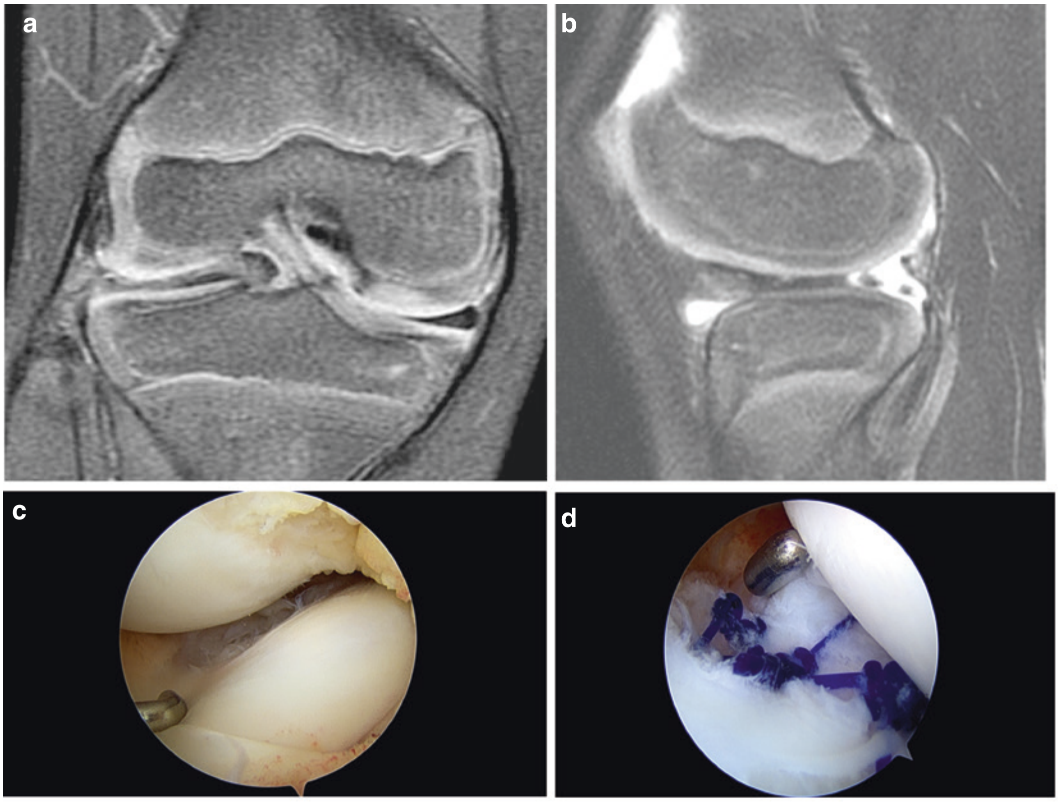

Fig. 9 **a** Coronal and **b** sagittal images of an 8-year-old boy show anterocentral shift type of the discoid lateral meniscus (arrows) in the right knee. **c** Arthroscopic photograph showing a complete type of discoid lateral meniscus with meniscocapsular junction tear at the lateral meniscus posterior horn around popliteal hiatus (arrow). **d** The 30° arthroscope inserted from posterolateral portal shows anatomic coaptation of the lateral meniscus posterior horn tear with 3 vertical sutures. (LFC, lateral femoral condyle; LM, discoid lateral meniscus)

With a 70° arthroscope inserted from the anteromedial portal and passed through the intercondylar notch to view the PL compartment, a shaver or rasp is introduced through the PL portal for debridement of both tear portions. The 70° arthroscope allows better visualization. Inserting and manipulating instruments without a cannula allows easier instrumentation maneuvering in the relatively restricted PL compartment. After preparation of the tear site, a 45 degree angled suture hook loaded with a No. 0 PDS is introduced through the PL portal, and a suture is performed starting from the tear site of the inner tear penetrating the most central portion in an inferior to superior direction. During this procedure, care must be taken not to damage the cartilage of the femoral condyle, as the hook is closest to the condyle during this procedure. Both ends of the No. 0 PDS are pulled out with a suture retriever through the PL portal. The superior end of the suture is marked with a straight haemostat, and the inferior suture end is left alone. A suture hook loaded with 2-0 MAXON or No. 0 Nylon is inserted through the PL portal and used to pierce the peripheral rim of the meniscus at the capsular side from the superior to inferior surface in the same manner. After both ends of the 2-0 MAXON or No. 0 Nylon are pulled out with a suture retriever through the PL portal, the superior end of the suture is marked with a straight haemostat. The inferior ends of the PDS and MAXON are held together and pulled out simultaneously through the PL portal using a suture retriever without soft tissue interposition between both ends. In doing so, any soft tissue (such as joint capsule or fat) entrapped between the sutures

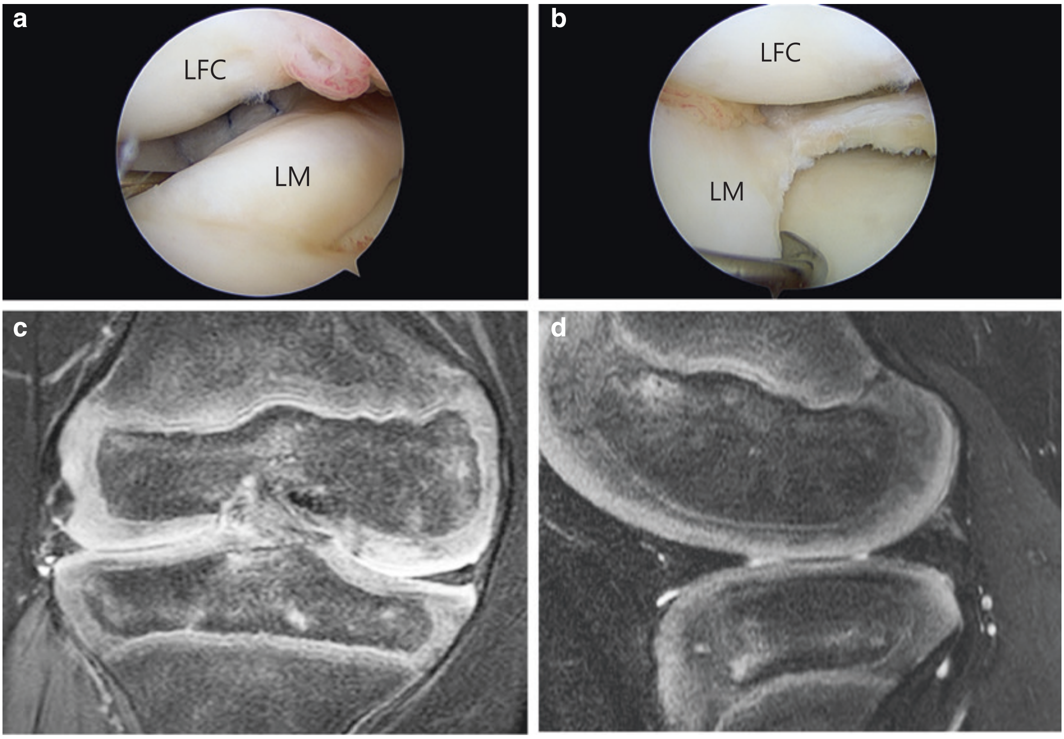

Fig. 10 **a** The 30° arthroscope inserted from anterolateral portal also shows anatomic coaptation of the lateral meniscus posterior horn tear with 3 vertical sutures. **b** After partial meniscectomy with repair, peripheral rim of lateral meniscus was preserved with 8-10 mm that is the similar size of the midbody of medial meniscus. **c**, **d** coronal and sagittal magnetic resonance imaging shows complete healing of the tear site with a lateral meniscus of normal shape at 6 months' follow-up. (LFC, lateral femoral condyle; LM, discoid lateral meniscus)

can be extracted. Next, the inferior end of the 2-0 MAXON is tied to the inferior end of PDS and the haemostat holding the superior end of the MAXON wire is then pulled. The PDS is passed through both sides of the meniscal tear and the MAXON wire is changed to a No. 0 PDS from the tibial to the femoral surface. Both ends of the PDS are held together and simultaneously pulled through the PL portal using a suture retriever. The SMC (Samaung Medical Center) knot is made outside and slipped inside the joint using a knot pusher through a previously inserted cannula in the PL portal. Depending on the size of a tear, additional sutures can be performed. Usually, 2 to 3 sutures are adequate for repair of longitudinal tears in the LMPH (Fig. 10).

Postoperative Care

The protocol for postoperative rehabilitation follows guidelines similar to those advocated for rehabilitation after ACL (ligamentous) reconstruction of the knee. The knee is immobilized in a full extension brace for 2 weeks. The affected knee joint is permitted a gradual range of motion, which is initiated with a range of motion/limited-motion brace, in which at least 90° of flexion is expected to be achieved during a 4- and 6-week postoperative period. Squatting, or deep flexion, greater than 120°, which places the repair site at risk for re-tear, is restricted for at least 8 weeks following the repair. Patients are also restricted for 6 months from sports activities that include jumping, cutting, or twisting manoeuvres. Crutches are used full time for the first 4 weeks postoperatively to protect the repair site from loading. Patients are allowed to initiate full weight-bearing by the (fourth) 6th postoperative week.

Outcomes

The traditional treatment for a symptomatic DLM is total meniscectomy via open or arthroscopic means [11, 33, 34, 37, 43]. Some reports have noted favorable long-term clinical results after total meniscectomy in children, but these studies examining the long-term radiographic results after total meniscectomy in children have shown early degenerative changes in 86% to 100% of cases. Recent reports have also found that peripheral instability in DLM patients occurs at a frequency of 38% to 88% [17, 28, 36]. Therefore, current treatment recommendations favor meniscal reshaping through partial meniscectomy with or without repair. In 2008 Ahn et al. [6] described short-term clinical results after arthroscopic partial meniscectomy in conjunction with meniscal repair for treating children with symptomatic DLM. This study showed 23 patients (28 knees) with a peripheral tear were treated by partial central meniscectomy in conjunction with peripheral suture repair. All patients were able to return to their previous life activities with little or no limitation, and no reoperation was required after an average follow-up of 51 months. So we concluded that arthroscopic partial meniscectomy in conjunction with the meniscal repair of the peripheral tear is effective for treating children with a symptomatic discoid lateral meniscus.

A few reports have found that the degree of meniscus resection was associated with the progression of degenerative changes. Kim et al. [25] compared the long-term radiologic outcomes of partial meniscectomy and total meniscectomy for torn DLMs with over 5 years of follow-up. Their results showed that partial meniscectomy led to better results. They concluded that the long-term prognosis after arthroscopic meniscectomy for a torn DLM was related to the volume of the meniscus removed, although the percentage of patients treated with total meniscectomy was high (64%) in their study. In 2015, Ahn et al. [2] reported the long-term clinical and radiographic results of arthroscopic reshaping with or without peripheral meniscus repair for the treatment of symptomatic DLM in 48 children. This study showed arthroscopic reshaping for symptomatic DLM in children led to satisfactory clinical outcomes after a mean of 10.1 years. However, progressive degenerative changes appeared in 40% of the patients. The subtotal meniscectomy group had significantly increased degenerative changes compared with partial meniscectomy with or without repair. Recent systematic review also demonstrated that the radiographic outcomes of DLM were better with partial meniscectomy with or without repair than with total meniscectomy, but their clinical outcomes were similar [29]. The findings thus suggest that meniscal preservation would be a better option than total meniscectomy for symptomatic DLM.

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Ramp Lesions

Romain Seil and Caroline Mouton

Abstract

Ramp lesions to the posterior horn of the medial meniscus have recently received increased attention due to their high prevalence in patients undergoing an anterior cruciate ligament reconstruction. The diagnosis of these lesions is rarely possible with preoperative imaging and quite limited with routine anterior arthroscopic inspection of the knee joint. Visual inspection of the posteromedial compartment of the knee joint should thus systematically be carried out via a trans-notch view and meniscocapsular structures directly probed with a needle or visualized via a posteromedial portal. While the clinical impact of ramp lesions is not yet well established, recent biomechanical studies have shown increased anteroposterior and rotational laxities when a ramp lesion is present. The latter may thus be a cause for postoperative persistent laxity potentially leading to the failure of ACL reconstructions. To date, it remains unclear whether all ramp lesions should be repaired as only a few publications report long-term outcomes after ramp lesion repair. This article provides an overview of the current knowledge on ramp lesions including their diagnosis, classification, biomechanical relevance as well as treatment and outcomes.

Keywords

Ramp lesion · Medial meniscus · Meniscocapsular · Meniscosynovial

Introduction

Over the last decade, awareness was raised on the posterior horn of the medial meniscus. The recognition of lesions in the meniscosynovial area, currently known as ramp lesions, has brought new perspectives on the treatment of anterior cruciate ligaments (ACL) injuries with which they are often associated. Although these lesions were firstly described by Hamberg and Gillquist in 1983 [1] as "A peripheral vertical rupture in the posterior horn of the medial or lateral meniscus with an intact body," it is only in the last few years that the interest of diagnosing and treating these lesions

R. Seil (✉) · C. Mouton
Department of Orthopaedic Surgery, Clinique d'Eich – Centre Hospitalier de Luxembourg, Luxembourg, Luxembourg
e-mail: rseil@yahoo.com

R. Seil
Sports Medicine Research Laboratory, Luxembourg Institute of Health, Luxembourg, Luxembourg

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has emerged. In a survey filled in by the directors of orthopedic sports medicine fellowship training programs in the United States [2], 61% of the respondents declared that their recognition of meniscal ramp lesions began less than 7 years ago.

As ramp lesions are difficult to diagnose with magnetic resonance imaging (MRI) [3] or through the usual anterolateral portal view during arthroscopy [4], they were often underdiagnosed in the past. To date, up to 86% of the directors of orthopedic sports medicine fellowship training programs routinely identify ramp lesions via inspection of the posteromedial meniscocapsular junction [2]. The prevalence of these previously unrecognized lesions was estimated at 9% in 2010 [5]. More recent studies found a prevalence between 20 and 30% [4, 6–11]. To date, it has been estimated that ramp lesions represent almost half of medial meniscus tears in ACL-injured patients [11, 12]. Leaving these lesions untreated may impact the integrity of the medial meniscus and hence of ACL reconstruction outcomes [13, 14]. Our understanding of the extent of the problem is, however, still at its early stage. This chapter aims to provide a comprehensive overview of the current knowledge existing on the classification, diagnosis, treatments, and outcomes of ramp lesions associated with ACL injuries.

Anatomy and Definition

Ramp lesions were first described by Hamberg and Gillquist in 1983 [1] as "A peripheral vertical rupture in the posterior horn of the medial or lateral meniscus with an intact body." They include tears at the posterior meniscocapsular junction and/or tears of the posterior meniscotibial ligament. Several terminologies have been used to describe these lesions such as meniscosynovial lesions, meniscocapsular separation, hidden lesions, and ramp lesions. We recommend exclusively the term "ramp lesion" with the following definition: a traumatic tissue disruption between the posterior horn of the medial meniscus and its meniscoligamentous and capsular junction located in the red-red zone 0 according to the Warren classification [15]. Both structures form a functional unit of which the anatomy, histology, and biomechanics are still poorly understood. The meniscoligamentous junction is the continuation of the circular collagen fibers of the medial meniscus. It runs oblique to the inferior edge of the posterior horn of the medial meniscus and has its other insertion on the posterior tibia at about 5–10 mm distal from the joint line. The dorsal area of the medial meniscus is also covered with the synovial membrane, which merges with the joint capsule. The posterior capsule also contains the insertion of the fibers of the semimembranosus muscle.

Classification

Thaunat et al. [16] were the first to propose a classification for ramp lesions based on the tear pattern and its association to a meniscotibial ligament tear. It considers the stability of the tear and can be used as an indicator for meniscal repair. Type 1 and 2 are stable lesions when probing. The former corresponds to a lesion behind the meniscotibial ligament. The latter is a partial superior lesion in front of the meniscotibial ligament that can be only diagnosed by a trans-notch approach. Type 3 is a partial inferior lesion, hidden with trans-notch approach, with low stability at probing. Type 4 and 5 are highly unstable at probing: type 4 being a complete lesion in front of the meniscotibial ligament, and type 5 a double lesion with associated meniscotibial ligament disruption. This classification nevertheless does not take into account the length of the lesion nor the stability of the capsuloligamentous complex during knee motion. Seil et al. [17], therefore, proposed an updated classification taking into account the latter criteria. It differentiates between complete lesions extending along the entire ramp and partial lesions being located either centrally or medially. The second criterion distinguishes between stable and unstable lesions. For the former, the capsuloligamentous complex adheres firmly to the posterior wall of the meniscus. Theoretically, these lesions have the potential to heal.

For dehiscent lesions, the capsuloligamentous complex is not adherent to the meniscus and may show a dehiscence or gap between the meniscus and the capsuloligamentous complex of the ramp, either in knee flexion or extension (Figs. 1 and 2).

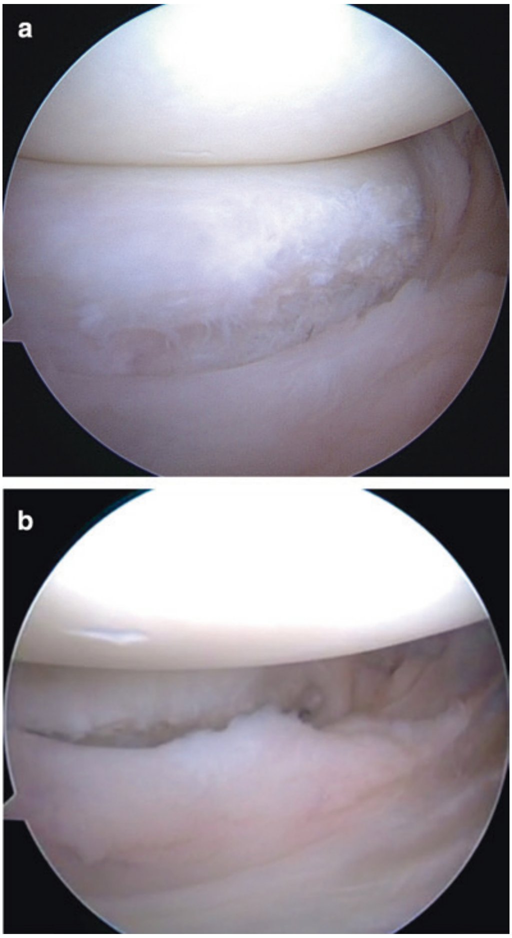

Fig. 1 **a** Posteromedial view of a left knee at 90° of flexion in a 28-year-old male patient with an ACL injury and a posteromedial ramp lesion. The picture shows a complete separation between the posterior wall of the medial meniscus and the capsuloligamentous ramp tissue, similar to a soft-tissue Bankart lesion in the shoulder. **b** Same knee as in Fig. 1a in an extended position. The separation between the posterior wall of the medial meniscus and the capsuloligamentous ramp tissue becomes clearly visible, indicating that an isolated repair from the anterior compartment has a high potential to fail. In such a case, the needle of the repair device may not grasp the capsuloligamentous tissue. Direct repair through a posterior portal is recommended in these cases

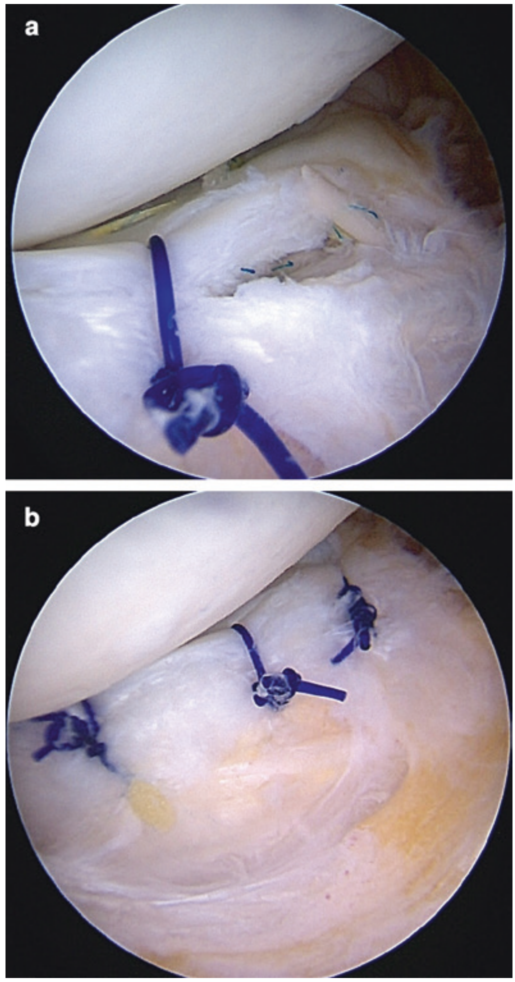

Fig. 2 **a** Posteromedial view of a left knee at 90° of flexion in a 21-year-old male patient with an ACL injury and a posteromedial ramp lesion. The figure shows a previously non-healed repair with a hybrid repair device. **b** View after removal of the repair device, debridement and direct suturing with 3 absorbable PDS-0 sutures

Prevalence of Ramp Lesions in ACL Injuries

In a study reporting data from six registries, medial meniscus lesions were reported to be present in 15–40% of ACL injuries [18]. The large variation observed between registries may be partly explained by the recent recognition of new lesions of the menisci observed during the ACL reconstruction. In the Luxembourgish registry, 45% of ACL injuries are associated with a medial meniscus tear [18] and 24% of all patients have a ramp lesion to the medial meniscus [8]. These findings suggest that about half of the lesions to the medial meniscus are ramp lesions and were previously undiagnosed. These data were confirmed by Kumar et al. [12]. In their study, 307 patients had a medial meniscus tear observed through MRI (36% of ACL injuries), including 127 ramp lesions (41% of all medial meniscus tears). In another study including 154 patients [11], 52% had a medial meniscus tear associated with the ACL injuries of which 56% were ramp lesions.

In 2001, Smith and Barrett [19] reported 575 meniscal tears in 476 out of 1021 patients who underwent an ACL reconstruction. Forty-seven percent of patients were thus concerned by a meniscal injury but only 3% of these tears concerned a peripheral tear in Zone 0. At this time, the posteromedial compartment was not systematically observed. The prevalence of these lesions has since then considerably grown (Table 1), with the exception of one of the latest publication of Cory et al. [20], where it is not clear whether a posteromedial approach was systematically performed, thus potentially introducing a bias. The increased prevalence highlights the great effort that was done in diagnosing ramp lesions over the last years as well as the increased awareness of the lesions in association with ACL injuries by orthopedic surgeons. The prevalence of isolated ramp lesions in the context of an uninjured ACL remains unknown.

Table 1 Prevalence of ramp lesions of the medial meniscus in ACL-reconstructed patients according to the year of publication

Study	Patients	Prevalence of ramp lesions (%)
Smith and Barrett [19]	575	3
Bollen [5]	183	9
Liu et al. [6]	868	17
Sonnery-Cottet et al. [4]	302	17
Peltier et al. [10]	41	15
Song et al. [21]	1012	16
Malatray et al. [9]	56	23
Seil et al. [8]	224	24
Edgar et al. [20]	337	13
Balasz et al. [22]	372	42

Biomechanical Consequences

Previous studies have suggested that ramp lesions are predisposed to an increased anterior translation and anteromedial rotatory subluxation of the knee. In cadavers, Ahn et al. [23] created large defects of the posterior horn of the medial meniscus at the meniscocapsular junction (mean length 2.8 cm, range 2.4–3.3 cm) in ACL-deficient knees. They found that ramp lesions in association with an ACL-deficiency led to a greater increase in anterior translation of the tibia compared to ACL-deficiency alone [23]. Recent cadaver studies also found a significant increase in internal and external rotation of the knee [24, 25] and in the pivot shift [25] after sectioning the posteromedial meniscocapsular junction in ACL-deficient knees. In all the cited studies, laxity was restored after ACL reconstruction and meniscocapsular lesion repair [23–25]. These findings confirm that the posterior horn of the medial meniscus is a secondary restraint to anterior tibial translation [26].

In vivo, Bollen [5] suggested, in a series of 17 ramp lesions, that such injuries may be associated with a mild anteromedial rotatory subluxation. In 275 patients, among which 58 (21%) displayed a ramp lesion in association with the ACL injury, Mouton et al. (https://pubmed.ncbi.nlm.nih.gov/31250053/) demonstrated that patients with an isolated ramp lesion were more likely to have a grade III pivot shift compared to patients with an isolated ACL injury and no ramp lesion. Song et al., however, suggested that a high-grade pivot shift test was not a risk factor for ramp lesions in non-contact ACL injuries [21]. In the latter publication, the discrepancy with the results from Mouton et al. may be explained by high-grade pivot shift grouped grade 2 and 3.

Associated Factors

Several factors have been found to be associated with ramp lesions of the medial meniscus. Yet, the causative nature of these factors remains to be proven. Gender and age have been reported to be associated with ramp lesions. Their prevalence was shown to be superior in males (by 7–8%) and in patients under the age of 30 [6, 7].

According to Seil et al. [8], ramp lesions are more likely to be observed in contact injuries (41% of ramp lesions in contact vs. 19% in non-contact injuries; $p<0.01$) and complete ACL tears (27% of ramp lesions in complete vs. 4% in partial ACL tears, $p<0.02$). The contact injury mechanism has recently been confirmed by Balasz et al. [22]. Revision ACL reconstruction, chronic injuries, a preoperative side-to-side difference laxity of more than 6 mm, and concomitant lateral meniscal tears have also been shown to be associated with ramp lesions [7]. The same authors found that ramp lesions were more common in chronic ACL tears (more than 6 weeks old) and that their prevalence increased significantly over time until 24 months after the injury where it stabilized [4, 6, 7].

Anatomic factors, such as the medial meniscal slope have been suggested to be a risk factor for ramp lesions in knees with ACL injury [21]. In this paper, the authors considered an increased medial meniscal slope when the observation was at least 1 standard deviation above the average (>3.2°). It remains unclear whether this threshold is optimal and further studies should try to establish the critical value of the meniscal slope.

Injury Mechanism

The injury mechanism of ramp lesions has not been fully established yet. Early MRI studies highlighted the fact that posteromedial tibial plateau edema was associated with injuries to the peripheral posterior horn of the medial meniscus [27]. At that time, the term “contrecoup injury” was created.

Newer imaging studies may provide an explanation as to how ramp lesions occur in ACL-injured knees [28–31]. These authors reproduced the position of the knee at the moment of the injury by superimposing the bone bruise areas on the femur and the tibia on MRI. Overlapping these areas allowed for a precise reproduction of the femoral position in relation to the tibia at the moment of the highest impact. This allows measurement of the displacement of the 2 bones with respect to each other. It was found that a subluxation of the medial tibiofemoral compartment was much more frequent as expected and occurred in 25–65% of ACL-injured knees. Anteroposterior displacements of up to 25 mm could be measured. This significant displacement makes the disruption of the meniscotibial attachment and the occurrence of ramp lesions plausible. Further biomechanical studies are needed to confirm these data.

Pre-arthroscopic Diagnosis

Currently, it seems impossible to diagnose ramp lesions during the clinical evaluation. The finding, that patients with an isolated ramp lesion in association with an ACL injury were more likely to have a grade III pivot shift compared to patients with an isolated ACL injury and no ramp lesion, may be of primary importance to suspect them during a clinical examination (https://pubmed.ncbi.nlm.nih.gov/31250053/). Nevertheless, in this series of 275 patients, only 23 out of 91 (33%) with a grade III pivot shift had a ramp lesion. This resulted in a positive predictive value (PPV) of only 25%, indicating that a grade III pivot shift is thus, poorly predictive of a ramp lesion. This may be explained by the fact that the grade III pivot shift is multifactorial and can be influenced by many other intra- and extraarticular bony and soft-tissue parameters [32].

The ability of Magnetic Resonance Imaging (MRI) to diagnose ramp lesions is also questionable. In 2010, Bollen [5] reported that none of the 17 ramp lesions they observed under arthroscopy could previously be diagnosed on

MRI. They suggested that the lesion reduces during MRI which is routinely performed with the knee in extension. This closes the posterior compartment of the knee, hence making the detection more difficult. The sensitivity of MRI to identify ramp lesions is significantly inferior compared to its sensitivity to detect tears of the medial meniscal body [11]. An irregular posterior meniscal outline (identified as a focal discontinuity or step-like contour deformities at the posterior margin of the medial meniscus posterior horn on T2 sagittal images) and perimeniscal fluid signal separating the meniscus and capsule may be indicative of a ramp lesion [33, 34]. Other suggested criteria include meniscal displacement, peripheral meniscal corner tears, increased perimeniscal signal intensity, fluid deep to the medial collateral ligament, and posteromedial bone bruise [35–38]. Publications assessing these criteria reported poor prediction of ramp abnormalities [38, 39], not only because the lesions are difficult to assess per se, but also because the series included a small number of cases [36, 39]. In a group of 78 patients including 7 ramp lesions, Yeo et al. [39] found that, when combining both the criteria of an irregularity at the posterior margin and a complete fluid filling sign, sensitivity of MRI to detect ramp lesions reached 100% and specificity 75%. Having none of these signs allowed us to exclude them (Negative predictive value—NPV: 100%), but the presence of one sign only was not particularly efficient in predicting a ramp lesion (PPV: 28%). In a group of 90 patients including 13 ramp lesions, Arner et al. [36] found similar predictive values (NPV—91–97% and PPV—50–90%) by combining perimeniscal fluid signal and posteromedial tibial plateau edema. Results were, however, highly dependent on the examiner. DePhillipo et al. [37] reported that 72% of 50 patients with ramp lesions had posteromedial tibial plateau edema on preoperative MRI. The PPV (55%) of such criteria is as low and was confirmed by another study [12]. It is important to mention that posteromedial tibial plateau edema may be highly influenced by the delay between the injury and the MRI. The edema can resolve, potentially resulting in a false negative MRI finding.

In summary, MRI seems to have the ability to exclude ramp lesions reliably, but their presence cannot be confirmed in an efficient manner. Further studies should deepen the potential to associate several identification criteria to improve the ability to detect the lesions on preoperative MRI.

Arthroscopic Diagnosis

An arthroscopic examination is the best method to diagnose ramp lesions. It requires a thorough and systematic inspection of the posteromedial compartment. Prior to this, a routine inspection and probing of the posterior horn of the medial meniscus should assess its integrity and its stability. Then, with the knee flexed at 90°, the arthroscope is passed through the intercondylar notch underneath the PCL to gain access to the posteromedial compartment. As the 30° arthroscope does not allow visualizing the entire zone of the ramp of the medial meniscus, a systematic percutaneous palpation of the meniscal ramp with a 21-G needle should be performed from a posteromedial approach (Fig. 3). Transillumination can help

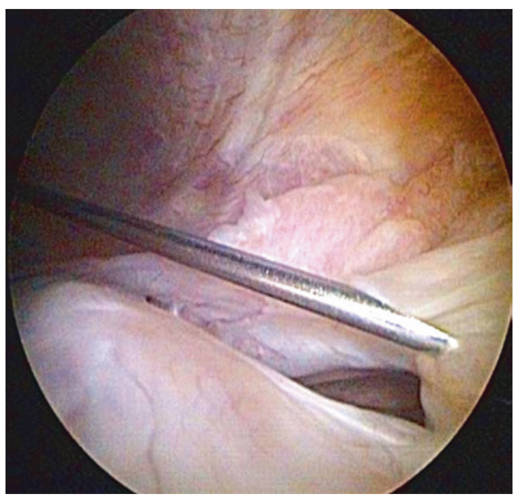

Fig. 3 Trans-notch view of the posteromedial compartment of a left knee at 90° of flexion. Arthroscopic inspection is improved by needle palpation. In this case, the tip of the needle lifts the capsuloligamentous ramp tissue away from the meniscal wall, allowing for a better visualization of the lesion

in identifying posteromedial structures at risks like the saphenous vein or nerve during this step. Visualization can be improved either by moving the foot in internal rotation, switching to a 70° arthroscope or through a direct visualization with a posteromedial arthroscopy portal [4, 40]. This is mandatory to be able to diagnose all ramp lesions of the medial meniscus because many of them can be missed through standard anterior inspection [4]. By using this three-step approach, Sonnery-Cottet et al. [4] were able to confirm the presence of a ramp lesion in 50 (40%) of the 125 observed lesions of the medial meniscus. Twenty nine of them (23%) were diagnosed through the trans-notch exploration of the posteromedial compartment. Seventeen percent ($n = 21$) could only be observed by probing the tear through a posteromedial portal, sometimes after a minimal debridement of a superficial soft-tissue layer with a motorized shaver. These results were later confirmed by Peltier et al. [10] who found 15% of new lesions with the use of the posteromedial portal.

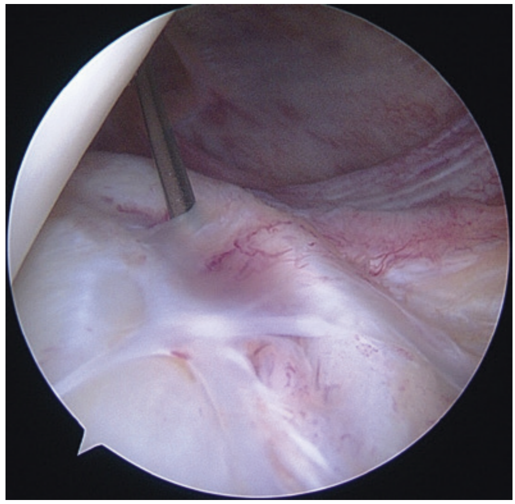

Fig. 4 Trans-notch view of the posteromedial compartment of a left knee at 90° of flexion in an ACL-injured patient, 6 weeks after the injury. The ramp lesion shows a partial synovialization. In this case, healing was not sufficient to leave the lesion unrepaired

Treatment

To date, there is no agreement on whether and when ramp lesions should be treated surgically and their natural history has not been sufficiently established. Due to their localization in the red-red zone of the meniscus and their vascularization, they have the potential to heal without surgical treatment (Fig. 4) [41]. However, the potential instability of the detached meniscocapsular structure during knee flexion and extension may refrain them to heal. In addition to this, there is a risk of tear extension and their persistent instability may put an ACL graft at risk for failure. On the other hand, the low morbidity of ramp repair favors the systematic suturing of these lesions.

The dynamic behavior of the ramp remains of great importance to decide whether to repair or not, especially if a dehiscence of the ramp can be observed during knee flexion and extension movements. Small and stable ramp lesions may have the potential to heal spontaneously as long as the knee joint is stabilized with an ACL reconstruction [41]. If the longitudinal extent of the tear exceeds 10 mm, a repair is definitively recommended. In case of a double lesion with a longitudinal tear of the meniscus body anterior to the ramp lesion, additional anterior repair should be performed.

If visualization appears difficult through the trans-notch inspection, either a second posteromedial or a transseptal portal can be considered during repair [42–45]. Repair technique is similar to an arthroscopic capsulolabral suture repair in the shoulder. It can be performed through the posteromedial portal with a curved needle (e.g., Spectrum, Conmed, Largo, FL, USA) (Fig. 5). After debridement of the meniscocapsular junction with a shaver, PDS-0 sutures are knotted every 5 mm and the stability of the repair is tested with a probe. Smaller distances may lead to a too frequent penetration of the meniscal tissue, hence weakening the structure of the meniscus. If additional anterior stabilization is required in more complex tears, traditional all inside repair techniques are used for complementary fixation of the posterior horn or

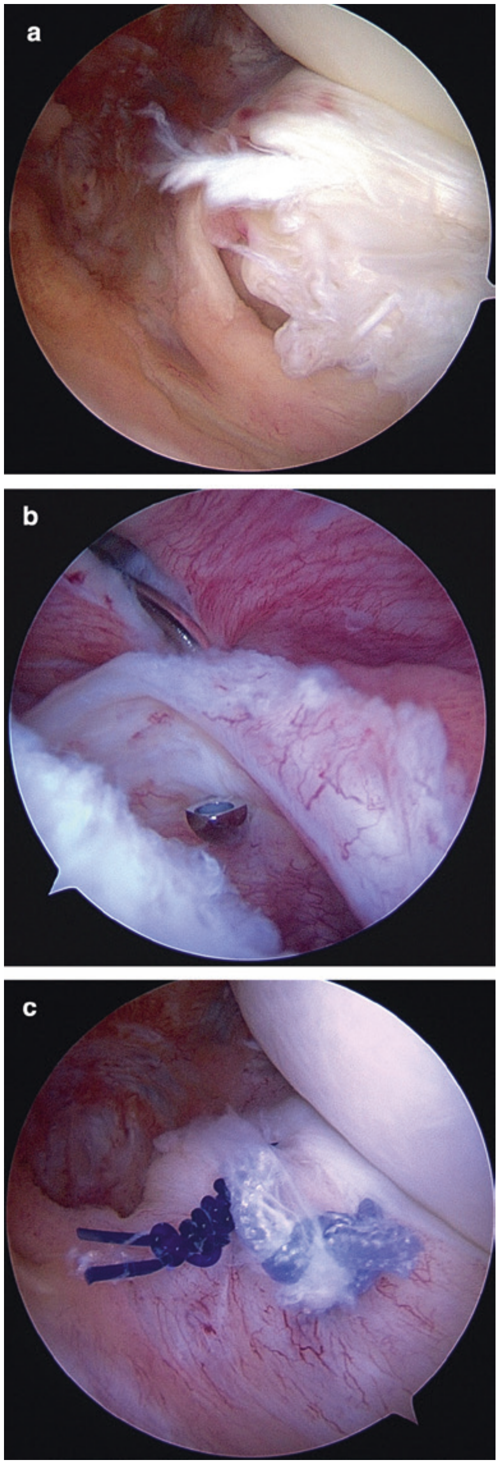

Fig. 5 **a** Posteromedial view of a left knee at 90° of flexion in a 14-year-old male patient with a pediatric ACL injury and a dislocated bucket handle tear of the medial meniscus. After reposition of the meniscus bucket handle a large separation between the posterior wall of the meniscus and the ramp tissue could be observed through direct posteromedial visualization. **b** Trans-notch view of the posteromedial compartment of the same patient as in Fig. 5a. The ramp tissue is grasped with a curved repair device (here: Spectrum, Conmed, Largo, FL, USA). **c** Same view as 5A in the same patient after ramp repair (here with 1 absorbable and 1 nonabsorbable suture). The ramp tissue has been nicely repositioned to the meniscal wall

outside-in techniques if a tear extends into the middle segment of the meniscus.

Rehabilitation

General principles of rehabilitation after meniscal repair are applied in these patients, including postoperative knee bracing in full extension for a period of 6 weeks. Weight-bearing is allowed as tolerated from day 1 after surgery. Knee flexion is limited to 90° for 6 weeks and deep squatting should be limited for 4–6 months.

Outcomes

Few short- or long-term outcomes have been reported in the literature after repair of ramp lesions. A recent systematic review reported that eight studies reported the outcome of ramp lesion repair in a total of 855 ACL-deficient knees [45]. Most of them were case series and four only considered stable ramp lesions. These studies offered various types of repair techniques. Overall, the Lysholm score increased from about 57–69 preoperatively to 88–94 postoperatively. Whether these results are similar to other types of meniscal repair or not should be further investigated in prospective studies.

Liu et al. [41] conducted a randomized controlled trial to evaluate the outcome of all-inside versus no repair (trephination only) among patients who underwent ACL reconstruction with stable meniscal ramp lesions (length < 1.5 cm and no excessive instability when probing the posterior horn of the medial meniscus). No significant differences could be found between the repair and no-repair groups in terms of meniscal healing rates, functional scores (Lysholm, IKDC), or knee stability. These findings were limited to stable tears and cannot be extrapolated to large or highly unstable ramp lesions.

In a recent retrospective study on 3214 ACL reconstructions, Sonnery-Cottet et al. found an overall incidence of ramp lesions of 24% [7]. A secondary analysis of 416 out of the 769 initial repaired ramp lesions, all being at a minimum of 2 years follow-up (45.6 months (range, 24.2–66.2 months)), showed an overall rate of secondary meniscectomies of 10.8%. The authors further divided these 416 patients into 2 groups with ACL reconstruction + anterolateral reconstruction and with ACL reconstruction alone. The first group had a two-fold lower risk of subsequent medial meniscectomy than the second group. These results suggest that anterolateral ligament reconstruction may have a protective effect on ramp lesion repair or at least on the medial meniscus. It should, however, be highlighted that the authors did not analyze the effect of the ramp repair itself and that the indication for meniscectomy was not clearly defined. The same group of authors published another study, more specifically oriented to ramp repair, and found that extended ramp lesions (extending to the midportion of the medial meniscus and requiring additional repair through the standard anterior portal) had an increased risk of failure (positive Barret's criteria and unhealed tear on MRI examination) than limited tears [46]. Failure occurred in 7% of the repairs. In five cases, recurrent tears were related to a new tear which was located anteriorly to the initial tear [46].

Conclusion

Currently, discrepancies in the definition of ramp lesions, as well as the variety of lesions and repair techniques analyzed in previous publications prevent from establishing clear guidelines on the optimal treatment for ramp lesions. It is now recognized that a systematic visualization of the posteromedial compartment under arthroscopy must be performed to diagnose such tears due to the lack of efficiency of pre-arthroscopic diagnostic with clinical examination or MRI. These tears can be expected in about 1 ACL-injured patient out of 4 and represent half of all medial meniscus lesions that can be observed during ACL reconstructions. They are more likely to be present in younger patients, with a grade III pivot, in contact injuries, in complete tears, and when a posteromedial plateau edema is observed at the preoperative MRI. To date, there is no real agreement on whether and when ramp lesions should be treated surgically. Length of the tear as well as the dynamic behavior of the ramp during knee flexion should be evaluated before making a decision. In case of a longitudinal extent of the tear above 10 mm, a dehiscence of the ramp should be an indication for repair. However, no clear recommendation can be made due to the lack of publication on postoperative outcomes.

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Root Tear: Epidemiology, Pathophysiology, and Prognosis

Byounghun Min and Do Young Park

Abstract

Meniscus root tears are disruptions in the ligamentous portion connecting the meniscus to the tibia. Its clinical presentation, pathophysiology, and treatment have only been explored fairly recently, compared to other meniscus tear types. Meniscus root tears are a unique clinical entity in that tears in this region disrupt the circumferential hoop tension of the whole meniscus, possibly leading to total meniscectomy-like consequences in the knee joint. Recent findings regarding pathophysiology and prognosis suggest that degenerative root tears follow a different clinical course compared to acute tears. A clear understanding of tear pathophysiology is required to accurately diagnose and choose patients that would benefit from surgical repair.

Keywords

Meniscus root tear · Circumferential hoop tension · Pathophysiology

B. Min (✉) · D. Y. Park
Orthopedics, Ajou University Hospital, Gyeonggi-do, Republic of Korea
e-mail: dr.bhmin@gmail.com

Meniscus root tears are defined as disruptions in the ligament tissue connecting the meniscus to the tibia. Meniscus root tears are a unique clinical entity in that tears in this region disrupt the circumferential hoop tension of the whole meniscus, possibly leading to total meniscectomy-like consequences in the knee joint. Unlike other meniscus tear types, it is only recently that meniscus root tears have been extensively characterized. In this chapter, we will explore recent findings in epidemiology, pathophysiology, and prognosis of meniscus root tears.

Epidemiology

Meniscus root tears most commonly present as medial meniscus posterior root tears, as chronic, degenerative tears associated with knee osteoarthritis. Reports find these tears during 10–21% of arthroscopic meniscus procedures [1–3]. The actual incidence of degenerative medial meniscus posterior root tears presenting with other osteoarthritis associated intra-articular pathologies are expected to be much higher, considering that root tears are a common finding in advanced osteoarthritis during total knee arthroplasty. Lateral meniscus posterior root tears on the other hand are less prevalent, found in approximately 3–7% of patients who undergo arthroscopic surgery. The occurrence of these tears

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increases up to 15% in anterior cruciate ligament deficient knees [1, 4–6]. The exact incidence of anterior root tears is unknown, as they are rarely described in the literature.

Anatomy

Grossly, each meniscus has two roots: anterior and posterior root. Each root connects the meniscus body to the tibial plateau. The anterior roots of the medial and lateral menisci are flat and have relatively planar insertions to the tibia. The anterior root of the medial meniscus inserts in line with the medial tibial eminence at an average of 7 mm anterior to the anterior cruciate ligament tibial insertion [7]. The anterior root of the lateral meniscus, on the other hand, inserts anterior to the lateral tibial eminence and adjacent to the insertion of the anterior cruciate ligament [7]. The posterior root of the lateral meniscus inserts posteromedial to the lateral tibial eminence apex and anterior to the posterior cruciate ligament tibial attachment [7]. The posterior root of the medial meniscus inserts posterior to the apex of the medial tibial plateau and anteromedial to the posterior cruciate ligament tibial attachment. The medial meniscus posterior root runs obliquely through its course with its tibial attachment sloping down the tibial edge where posterior cruciate ligament insertion occurs [8]. The posterior, sheet-like fibers of the medial meniscus posterior root have been termed "shiny white fibers" due to their appearance during arthroscopy via posterior portals [9].

Microstructure-wise, the normal meniscus root is a ligament-like structure that differs from fibrocartilage tissue of the meniscus body [10]. Collagen bundles of the meniscal roots mostly run parallel to its longitudinal axis [10]. Meniscus roots are mostly composed of collagen type 3 and collagen type 1 extracellular matrix. The tibial insertions sites exhibit classic enthesis characteristics, with tissue transitioning from ligament tissue to uncalcified and calcified fibrocartilage, and ultimately bone (Fig. 1) [8].

Function of Meniscus Roots

Meniscus roots act to stabilize the meniscus and transmit loads from femoral condyles to tibia [5]. The meniscus contains circumferential collagen fibers that resist extrusion during load bearing from femoral condyles. This resistance toward extrusion is also known as "hoop stress." Meniscus roots in turn complete the circumferential collagen structure of the meniscus. Consequently, a tear in the posterior root results in a 25% increase in femur-tibia peak contact pressure on the knee, compared to knees with intact roots, similar to a total meniscectomy [5].

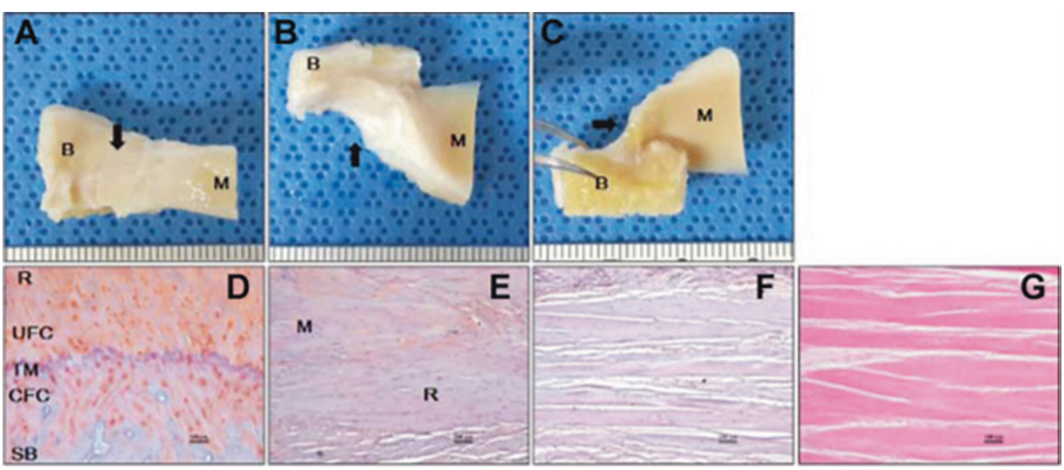

Fig. 1 From (Park et al., American Journal of Sports medicine, 2015)

This increase in peak contact pressure returns to normal values upon root repair. Root tears also increase external rotation and lateral translation of the tibia relative to the femur and result in varus alignment [11].

Pathophysiology

Root tears occur in two different types of settings, one as a result of an acute traumatic event, and the other as a result of a degenerative process within the knee joint such as osteoarthritis.

Injury resulting in an acute meniscus root tear usually occurs with the knee in hyperflexion, such as during squatting [12]. Medial meniscus posterior root tears have also been associated with multi-ligament knee injuries [13]. Anterior roots and lateral meniscus posterior roots are relatively more mobile compared to medial meniscus posterior roots [14]. Consequently, root tears other than medial meniscus posterior roots are much less commonly encountered [15].

Degenerative root tears, overwhelmingly occurring in the medial meniscus posterior root, have a different pathophysiology compared to acute tears. Risk factors for degenerative root tears of the medial meniscus overlap with those of knee osteoarthritis, including increased age, female sex, increased BMI, varus alignment, and decreased sports activity levels [1–3]. Medial meniscus posterior roots also receive more compressive stress and are relatively less mobile compared to other roots due to the root's firm adhesion with the medial collateral ligament and posterior capsule, making this region more susceptible to chronic tears [14, 16–18]. Our recent study characterizing medial meniscus posterior root changes in normal, and untorn, partially torn, and completely torn roots from osteoarthritic knees suggest that the pathophysiology of degenerative medial meniscus roots closely resembles that of degenerative rotator cuff tears [8]. The normal root is devoid of fibrocartilage except in areas of root-to-bone interface. We have found fibrocartilage formation along with other degeneration related markers within the roots correlating with the degree of tear (Fig. 2). Repetitive, compressive stress resulting from osteoarthritic changes may cause ectopic fibrocartilage formation in the root, a known adaptive change in tendons suffering from pathologic compression and impingement. Fibrocartilage formation makes the tissue more resistant to compressive stress, yet less resistant to tensile stress. While the medial meniscus root resists compression stress, the main function is to resist tensile stress from the hoop tension of the meniscus body. The degenerated, fibrocartilage region of the root may, therefore, be more susceptible to tear, usually in a radial direction (Fig. 3). This unique pathophysiology of degenerative root tears is clinically important as the tissue of tear margins differ from acute tears and may not be suitable for repair.

Prognosis

The natural history of root tears is not well-defined. Theoretically, non-operative treatment of meniscus root tears may exacerbate meniscus extrusion and joint space narrowing of the involved compartment. Such prognosis, however, is not always clear. In one study involving patients with degenerative medial meniscus tears, the degree of meniscus extrusion was similar in knees with and without root tears [12]. Another study evaluating subjective knee scores and degree of joint space narrowing in lateral meniscus posterior root tears left untreated during anterior cruciate ligament reconstruction found that there was progression of joint space narrowing of about 1 mm compared to control knees at 10 years follow-up but no difference in subjective scores [19].

Operative treatment for meniscal root tears includes meniscectomy and meniscus root repair. Partial meniscectomy may be indicated in symptomatic patients with chronic root tears and concomitant grade 3–4 cartilage lesions who do not respond to non-operative treatment. In a previous retrospective study assessing 67 patients with a mean follow-up of 56.7 months, partial meniscectomy for medial meniscus posterior root tears resulted in improvement of subjective knee

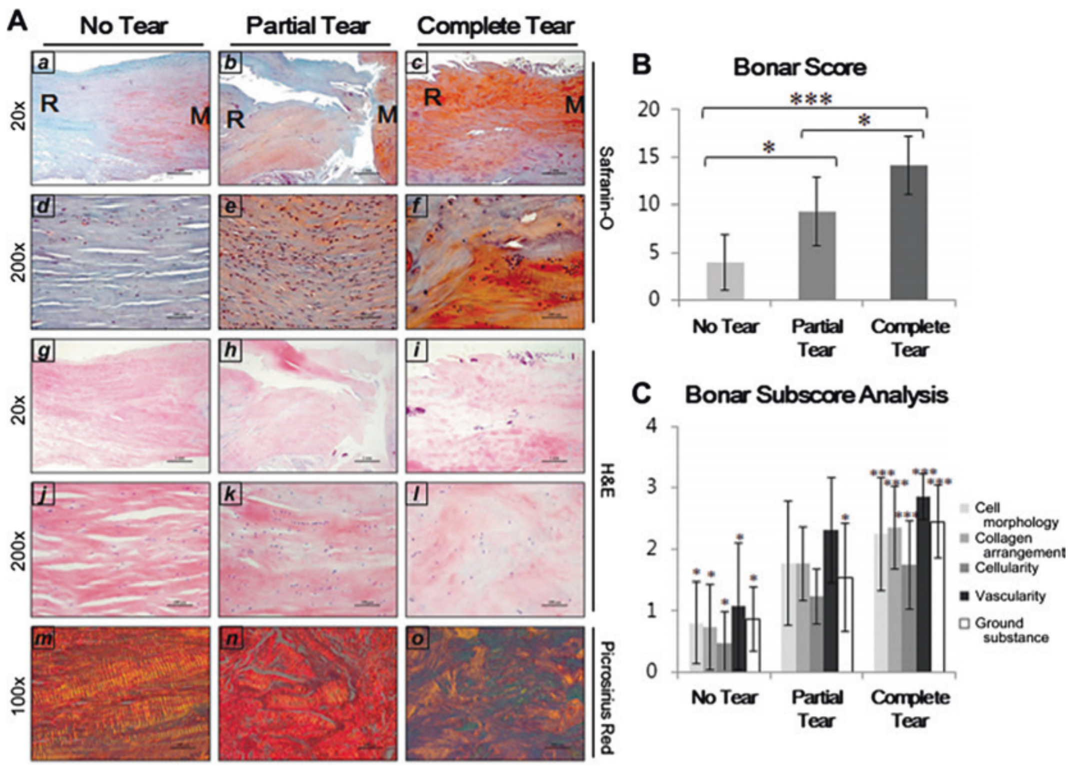

Fig. 2 From (Park et al., American Journal of Sports medicine, 2015)

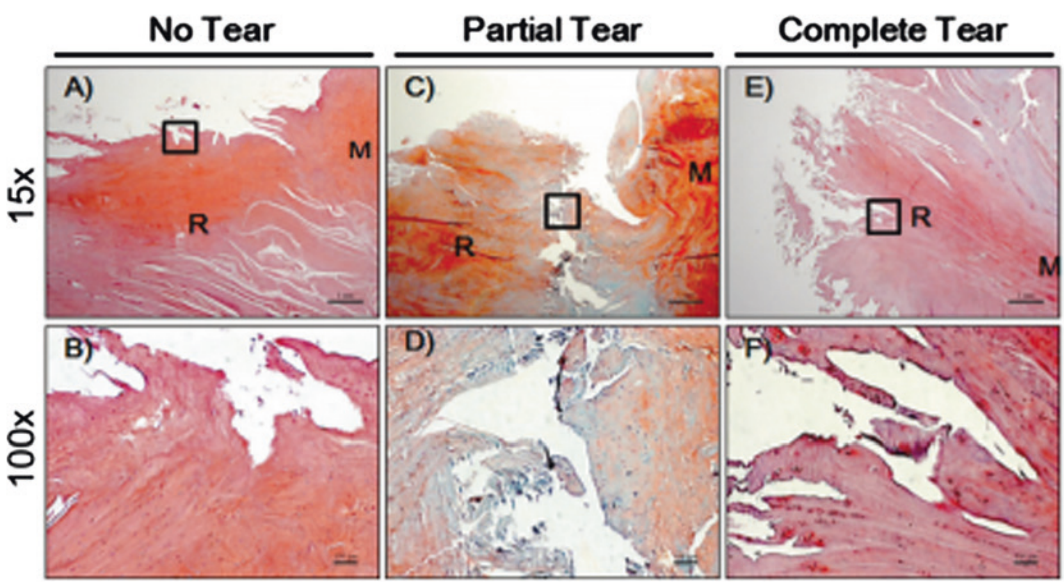

Fig. 3 From (Park et al., American Journal of Sports medicine, 2015)

scores but also resulted in progression of radiographic arthritis [3] Another retrospective study comparing 58 patients with medial meniscus root tears who received either partial meniscectomy or root repair showed that although both procedures resulted in subjective knee score improvements, the repair group showed less progression of osteoarthritis at 4 years follow-up [20]. Meniscal root repair, on the other hand, may be indicated in symptomatic patients with acute tears, or with chronic tears that are without severe concomitant cartilage lesions (< grade 3). Several studies have shown subjective knee score improvements, reduction of extrusion, and cessation of degeneration progression in the short term [20–24]. Controversy exists, however, in regard to patient selection, timing of surgery, and method of repair. Not all root repairs heal, as demonstrated in previous studies assessing the repair efficacy by MRI or second look arthroscopy [22, 23]. Further understanding of tear pathogenesis, healing mechanism, and natural history of root tears should improve the overall prognosis of root tear treatment.

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Root Tear: Surgical Treatment and Results

Kyu Sung Chung

Abstract

A complete radial tear of the meniscus posterior root, which can cause a state of total meniscectomy via loss of hoop tension by disrupting the critical circumferential fibers, requires that the torn root be managed. Several regimens for meniscal root tear have been introduced, including conservative treatment, meniscectomy, and root repair. In root tear, conservative treatment or meniscectomy have been considered the "traditional" treatment, and has been widely used for a long time. Both managements can provide symptomatic relief, but most cases with both managements ultimately progress to degenerative arthritis. Recently, interest in root repair has increased, because the repair of meniscal root has a positive effect on functional restoration of meniscus by restoring hoop tension. A recent international consensus statement has acknowledged the effectiveness of root repair with several evidences taken form biomechanical and clinical studies with goals of restoring the structure and function of the meniscus. However, there are several challenges to overcome, especially how to get firm healing of the repaired root, how to minimize meniscus extrusion, and how to prevent progression of arthritis completely. This chapter demonstrates surgical technique of root repair and reviews clinical results of root repair focusing on several considering factors.

Keywords

Meniscus · Root tears · Repair

The meniscus is composed of a complex interconnecting network of collagen fibers, proteoglycans, and glycoproteins [1]. The collagen fibers are oriented primarily in a circumferential direction but are also interconnected by radial fibers that allow the meniscus to function as a unit. Acting through their anterior and posterior bony attachments, the collagen fibers stretch under axial load building up internal hoop stress that absorbs and redistributes the forces transmitted to the joint. This mechanical system keeps the peak forces at an acceptable level [2].

Meniscus root is the meniscus tissue attached to tibial plateau anteriorly and posteriorly [3]. Recent anatomical study proved that the meniscus posterior root as an insertional ligament firmly attaches the to the tibial plateau, and it

K. S. Chung (✉)
Department of Orthopaedic Surgery and Sports Medical Center, Seoul Paik Hospital, College of Medicine, Inje University, 9, Mareunnae-ro, Jung-gu, Seoul, Republic of Korea
e-mail: drokokboy@hanmail.net

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transitions into the fibrocartilaginous structure of the meniscal body [4].

Meniscus root tears are defined as an avulsion injury or radial tear occurring in its bony attachment [5]. Among them, medial meniscus posterior root tears (MMPRTs) defined as injury in posterior bony attachment have commonly happened in Asian people [6–8]. It is assumed that their lifestyle behaviors, including frequent squatting and sitting on the floor with the legs folded may cause root tears. On the other hand, lateral meniscus posterior root tears have happened in anterior cruciate ligament injury and they are highly associated with acute traumatic injury [9, 10]. Detachment of the posterior root completely disrupts the continuity of the circumferential fibers, leading to loss of hoop tension, loss of load sharing ability, and unacceptable peak pressures [11–13]. It has been shown that a posterior root tear has the same consequences as a total meniscectomy and the pathological loads lead to degenerative arthritis [11]. Consequently, this series of processes leads to degenerative arthritic changes.

The "traditional" treatment for MMPRTs is conservative treatment or meniscectomy; it has been widely used for a long time. Both managements can provide symptomatic relief, but most cases in which conservative treatment [14–16] or meniscectomy [17–19] has been performed ultimately progress to degenerative arthritis. Several biomechanical studies of root repair addressed that root repair restores the hoop tension of the meniscus and its ability to dissipate forces, which can slow the progression of arthritis [11–13]. Recently, meta-analysis or systematic review reported that root repair showed satisfactory clinical and radiologic outcomes which can slow the progression of arthritis in most cases [8, 20]. Encouraging clinical results from root repair over the last decade have increased interest in this procedure.

However, there are several factors considered in applying root repair. Based on previous evidences, root repair showed a limited efficacy in complete prevention of arthritic changes although it slows down the arthritic changes [7]. In this regard, there are several challenges to overcome, especially how to get complete healing, how to get complete reduction of meniscus extrusion [21], how to manage concomitant cartilage problem, which degree is acceptable mechanical alignment to achieve favorable outcome, and which prognostic factors can achieve favorable outcome. In facing those challenges, we will continue to improve our surgical and perioperative management to restore root tears back to normal knee joint. This chapter demonstrates surgical technique of root repair and reviews clinical results of root repair focusing on several considering factors.

Surgical Procedures of Repair of Medial Meniscus Posterior Root Tear Using Modified Mason-Allen Stitch

Recently, my preferred technique is arthroscopic transtibial root repair using modified Mason-Allen stitch with locking mechanism [22]. The arthroscope is introduced through the anterolateral (AL) portal, and the working instruments is introduced through the anteromedial (AM) portal. Arthroscopic examination is routinely performed to confirm root tear or abnormality of intra-articular structures.

If MMPRT is confirmed on arthroscopic examination, the superficial medial collateral ligament (sMCL) is released to get a sufficient working space. The release of the sMCL was achieved using a periosteum elevator directed toward the distal attachment area of the sMCL via 3-cm longitudinal skin incision made at the anteromedial aspect of the proximal tibia [23]. The distal attachment of sMCL release was performed completely via subperiosteal stripping into 2 directions, distal direction (from just inferior of the pes anserinus attachment to the distal tibial attachment of the sMCL) and posteromedial direction (the posteromedial crest of the proximal tibia beneath the tibial attachment of the posterior oblique ligament and the proximal attachment of the sMCL), while preserving the deep medial collateral ligament, proximal sMCL, and posterior oblique ligament (Fig. 1).

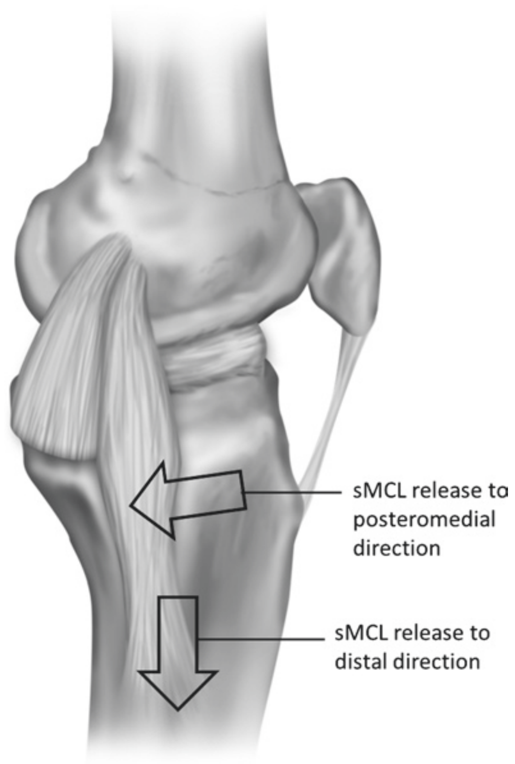

Fig. 1 The release of the superficial medial collateral ligament (sMCL) was achieved using a periosteum elevator directed toward the distal attachment area of the sMCL via 3-cm longitudinal skin incision made at the anteromedial aspect of the proximal tibia. The distal attachment of sMCL release was performed completely via subperiosteal stripping into 2 directions, distal direction (from just inferior of the pes anserinus attachment to the distal tibial attachment of the sMCL) and posteromedial direction (the posteromedial crest of the proximal tibia beneath the tibial attachment of the posterior oblique ligament and the proximal attachment of the sMCL), while preserving the deep medial collateral ligament, proximal sMCL, and posterior oblique ligament

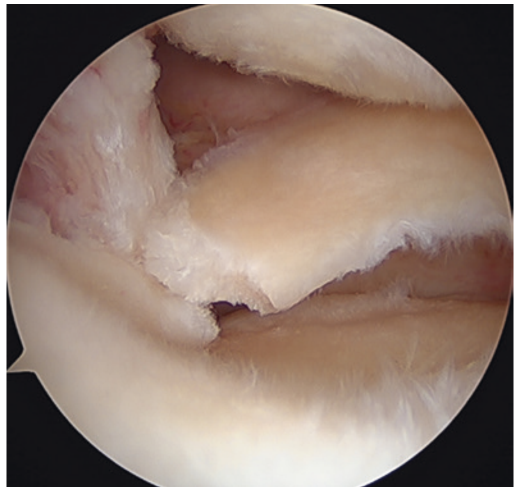

Fig. 2 Confirming of root tear

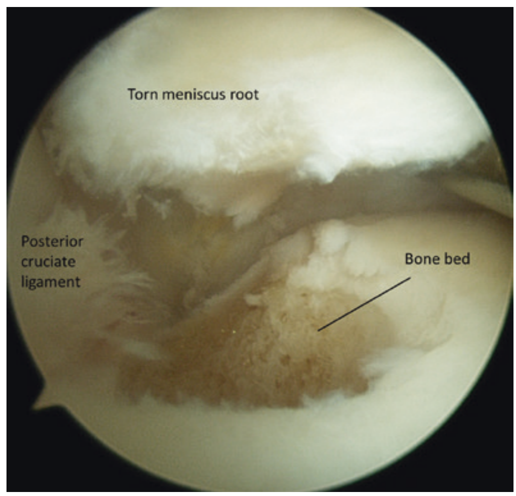

Fig. 3 Making a bone bed at the native root insertion site

After getting larger working space and more clear visualization by the sMCL release, root tear (Fig. 2) and landmarks relevant to the insertion of the medial meniscus, including the PCL insertion point, medial tibial spine, and articular margin of the tibial plateau, should be identified by arthroscopy. A meniscus resector and shaver are used to remove fibrous tissue and get fresh meniscus tissues.

Next, a curette is inserted through the AM portal to make a bone bed at the native root insertion site (Fig. 3). The bone bed is positioned at just medial side of posterior cruciate ligament and just posterior side of medial eminence of tibia [3]. This is an important procedure to get bone-to-meniscus healing, so larger bony bed is recommended to improve healing potential.

Next, a crescent-shaped suture hook (Linvatec; Largo, FL, USA) loaded with No. 1 polydioxanone (PDS; Ethicon; Somerville, NJ, USA) is then passed through the AM portal.

The detached portion of the medial meniscus posterior horn is penetrated by the sharp tip of the suture hook at a point 5 mm medial to the torn edge in a vertical direction from the femoral side to the tibial side (Fig. 4). Then, No. 1 PDS is advanced through the suture hook to the tibial side and taken out through the AM portal using a suture retriever. The other strand with Maxon^{TM} (Covidien; Minneapolis, MN, USA) to differentiate PDS inserted previously is placed in a position inside that of the first suture, in an identical manner via the same portal (Fig. 5). The superior ends of the two sutures are then tied outside the portal, and the inferior end of the Maxon^{TM} suture is pulled out. Using the shuttle relay method, the Maxon^{TM} suture is exchanged with the PDS suture so that the horizontal loop is completed (Fig. 6). A crescent-shaped suture hook loaded with No.1 PDS is again passed through the AM portal, and a simple vertical stitch is made that overlays and crosses the horizontal suture (Fig. 7). Both ends of the suture are then taken out through the AM portal; the resulting cruciate-shaped stitch constitutes a modified Mason-Allen stitch. If the quality of the root tissue is good and if there is a sufficient space to insert more PDS, additional vertical suturing may be performed.

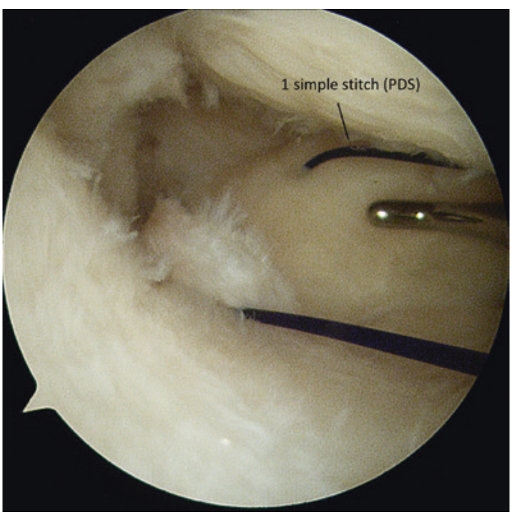

Fig. 4 Inserting PDS suture by crescent-shaped suture hook

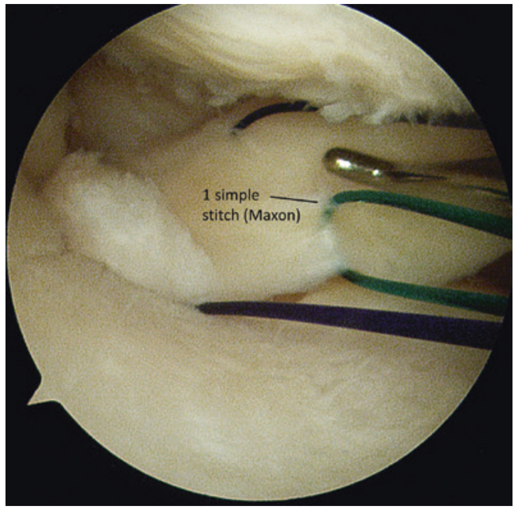

Fig. 5 Inserting Maxon suture by crescent-shaped suture hook

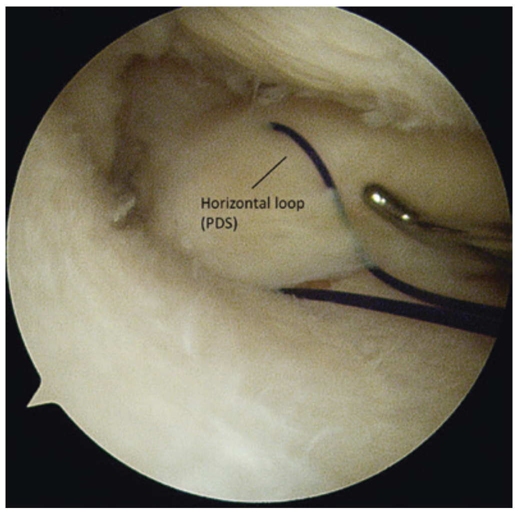

Fig. 6 Using the shuttle relay method, the Maxon suture is exchanged with the PDS suture so that the horizontal loop is completed

Next, soft tissue is detached from the previously incised area to allow for sMCL release to make a tibial tunnel. An anterior cruciate ligament reconstruction tibial tunnel guide (Linvatec; Largo, FL, USA) is inserted through the AM portal, with its tip placed in contact with normal attachment site of meniscal root. A Kirschner wire (K-wire) is then passed through

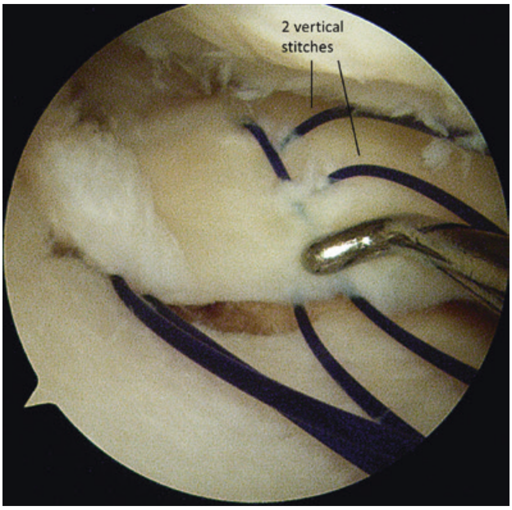

Fig. 7 Inserting simple vertical stitches (overlaying and crossing the horizontal suture)

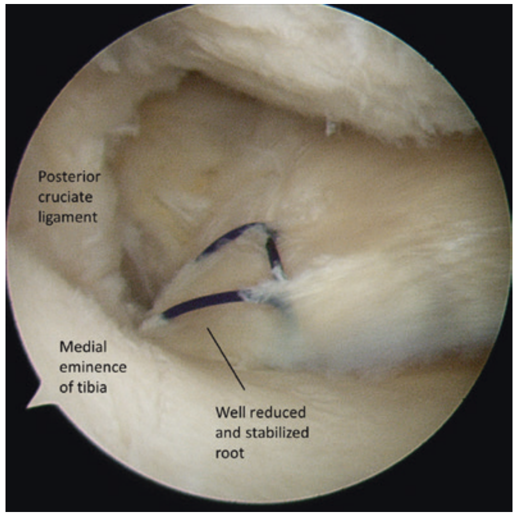

Fig. 9 The meniscus is reduced and stabilized when the ends of the sutures are pulled through the tibial tunnel

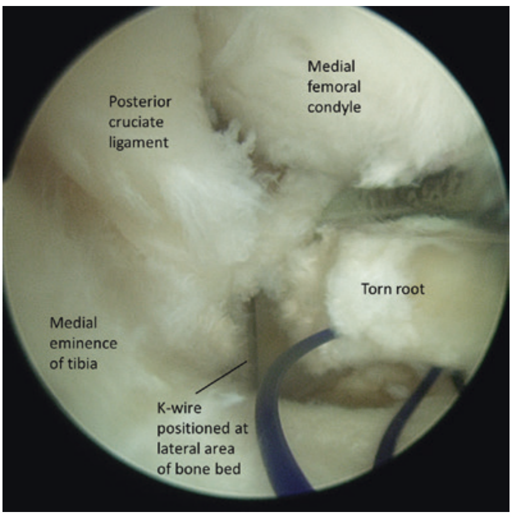

Fig. 8 K-wire is visualized directly using an arthroscope. The K-wire tip should be positioned at far lateral area of bone bed and just medial area of the posterior cruciate ligament. After confirming suitable tunnel position, the K-wire is pulled back through

the guide, with the K-wire is visualized directly using an arthroscope (Fig. 8). The K-wire tip should be positioned at far lateral area of bone bed and just medial area of the posterior cruciate ligament. After confirming suitable tunnel position, the K-wire is pulled back through.

Next, the metal wire with the loop is then inserted into the tibial tunnel (from anterior opening of tibial tunnel) until its tip can be seen; it is then taken out through the AM portal using a suture grasper.

In the next step, the metal wire is taken out from the tibial tunnel together with the ends of the PDS strands after properly engaging PDS strands within the metal wire loop. The meniscus is reduced and stabilized when the ends of the sutures are pulled through the tibial tunnel (Fig. 9).

The suture ends are then tied over an Endobutton (Smith & Nephew; Andover, MA, USA), which is placed under the periosteum overlying the anteromedial tibial cortex with the knee at full extension (Fig. 10).

Finally, an arthroscopic evaluation is performed to confirm condition of the torn meniscal root and the entire medial meniscus.

Postoperative Rehabilitation

Lifestyle modifications aimed at avoiding deep knee flexion should be recommended for all patients. Range of motion (ROM) exercises are

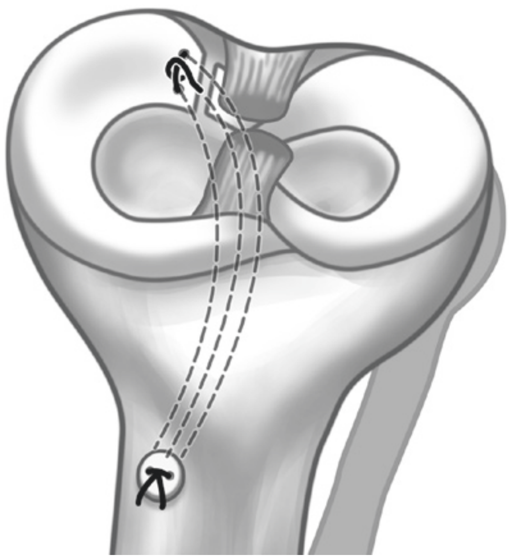

Fig. 10 The suture ends are then tied over an Endobutton which is placed under the periosteum overlying the anteromedial tibial cortex with the knee at full extension

performed after 3 weeks postoperatively, and progressive ROM exercises can be performed, at up to 90° flexion, 6 weeks postoperatively. Toe touching using crutches commence immediately after surgery, with the brace locked to allow for full extension of the knee joint in the first 3 postoperative weeks. Progressive partial weight-bearing exercises commence 3 weeks postoperatively. Full weight-bearing and progressive closed kinetic chain strengthening exercises are permitted 6 weeks after surgery. Light running is permitted after 3 months, and sports participation is allowed at 6 months.

Clinical Results of Root Repair

Based on meta-analysis in MMPRTs [8, 20], root repair resulted in significant improvements in the postoperative clinical subjective scores compared with the preoperative status. However, in terms of progression of Kellgren-Lawrence grade (KL grade) and cartilage status, it did not prevent the progression of arthrosis completely [7, 24]. Progression of arthritis would be associated with several considering factors, such as remained meniscus extrusion and healing status.

Several studies reported clinical results of repair in MMPRTs and Table 1 summarizes clinical and radiological outcomes after root repair (Ahn et al. [25], Jung et al. [26], Moon et al. [27], Kim et al. [28], Seo et al. [29], Kim et al. [30], Lee et al. [31], Lee et al. [32], Chung et al. [7], LaPrade et al. [33], Lee et al. [34]). However, most of them are based on small sample size, short-term follow-up examinations, and retrospective non-randomized case series. This chapter demonstrates specific clinical and radiological results of root repair focusing on several considering factors, such as remained meniscus extrusion and healing status.

1. **Options of surgical procedures of root repair**

There are several options to perform root repair; how to approach (anterior portal or posterior portal), how to repair (pullout repair or suture anchor repair), suture materials (non-absorbable or absorbable sutures), and suture fixation methods (non-locking or locking sutures). Based on meta-analysis in MMPRTs [8], most common technique is arthroscopic transtibial pullout fixation with non-locking mechanism through anterior portal.

(a) Anterior portal versus Posterior portal

When applying root repair, anterior portal approach is commonly used because anterior portal approach is easier to approach in posterior root attachment area than posterior portal approach. However, especially in patients with tight knee, it is difficult to visualize and use instruments to address meniscal pathologies in posterior compartment. The aggressive force needed to open the medial compartment in tight knee may result in unwanted complications such as rupture of the MCL or fracture of the femur. Thus, periosteal detachment of distal sMCL or pic-crust release of sMCL is needed to overcome narrow medial compartment. Chung et al. reported that the release of the distal attachment of the sMCL during root repair did not result

Table 1 The clinical characteristics and outcomes of the eligible studies

Study	Study design (level of evidences)	Repair technique	Tear location	No. of patients	Mean age (years)	Mean follow-up (months)	Mean Lysholm score		Progression of KL grade	Progression of cartilage grade		Mean Meniscus extrusion (mm)		Healing
							Before	After		Method, %		Before	After	Method, %
Jung et al. [26]	Case series (IV)	Suture anchor	Medial	13	53.2	30.8	69.1	90.3	No data	No data	No data	3.9	3.5	MRI complete: 50% (5/10) Partial: 40% (4/10) No: 10% (1/10)
Moon et al. [27]	Case series (IV)	Pullout (simple stitch), PDS	Medial	51	59	33	48.3	83.2	No data	MRI, 7% (2/31)		3.6	5.9	MRI complete: 90.3% (28/31) Partial: 9.7% (3/31) No: 0%
Kim et al. [28]	Comparative study (III) (pullout vs. suture anchor)	Pullout (simple stitch), Ethibond	Medial	22	53.2	25.9	54.3	92.5	14% (3/22)	MRI, 18% (3/17)		4.3	2.1	MRI complete: 65% (11/17) Partial: 35% (6/17) No: 0%
		Suture anchor	Medial	23	52.8	26.8	55.4	93.2	9% (2/23)	MRI, 21% (3/14)		4.1	2.2	MRI complete: 85% (12/14) Partial: 15% (2/14) No: 0%
Seo et al. [29]	Case series (IV)	Pullout (simple stitch), PDS	Medial	21	55.4	13.4	56.1	83	5% (1/21)	2nd look arthroscopy, 9% (1/11)		no data		2nd look arthroscopy complete: 0% Lax: 45% (5/11) Scar: 36% (4/11) No: 19% (2/11)
Kim et al. [30]	Comparative study (III) (vs. meni-scectomy)	Pullout (simple stitch), PDS	Medial	30	55.2	48.5	56.8	85.1	30% (9/30)	MRI, 20% (6/30)		3.13	2.94	MRI Complete: 56.7% (17/30) partial: 36.7% (11/30) No: 6.7% (2/30)

Table 1 undefined

Study	Study design (level of evidences)	Repair technique	Tear location	No. of patients	Mean age (years)	Mean follow-up (months)	Mean Lysholm score		Progression of KL grade	Progression of cartilage grade	Mean Meniscus extrusion (mm)		Healing
							Before	After		Method, %	Before	After	Method, %
Lee et al. [31]	Case series (IV)	Pullout (simple stitch), Ethibond	Medial	20	51.2	31.8	57	93.1	5% (1/21)	2nd look arthroscopy, 0% (0/10)	No data		2nd look arthroscopy Complete: 100% (10/10) Partial: 0% No: 0%
Lee et al. [32]	Comparative study (III) (vs. simple stitch)	Pullout (Mason-Allen stitch), PDS	Medial	25	55.7	24.1	57.4	87.6	8% (2/25)	MRI, 24% (6/25)	4.7	4.1	MRI complete: 60% (15/25) Partial: 36% (9/25) No: 4% (1/25)
Chung et al. [7]	Comparative study (III) (vs. meni-scectomy)	Pullout (simple stitch), PDS	Medial	37	55.5	67.5	52.3	84.3	68% (25/37)	No data	No data		No data
Lee et al. [34]	Case series (IV)	Pullout (simple stitch), PDS	Medial	56	53.3	40.6	48.7	81.5	41% (23/56)	No data	No data		2nd look arthros-copy Stable: 69.7% (23/33) No: 30.3% (10/33)
LaPrade et al. [33]	Case series (IV)	Pullout (simple stitch), Fiberwire	Medial	35	41.0	30	54	84	No data	No data	No data		No data
			Lateral	15	32.2		35	75					
Ahn et al. [25]	Case series (IV)	All-inside (sim-ple stitch), PDS	Lateral	25	28.8	18	62.3	92.9	No data	No data	No data		2nd look arthroscopy Stable: 88% (8/9) No: 12% (1/9)

in residual instability and complication [23]. However, some surgeons may have concerns of sMCL injury and hesitate to perform sMCL release. In this situation, posterior transseptal portal approach is an alternative method to approach and visualize posterior root area without sMCL release procedures [34].

(b) Transtibial pullout repair versus Suture anchor repair

Among root repair studies, few studies with suture anchor fixation were reported. In comparative study between suture anchor repair and transtibial pullout repair in MMPRTs [28], both techniques showed symptomatic improvement and no significant differences in KL grade in mean follow-up duration of 25.9 months. In follow-up magnetic resonance imaging (MRI), complete structural healing was seen in 50% of pullout fixation group and 52% of suture anchor fixation group. Mean meniscus extrusion of 4.3 mm in pullout fixation group and 4.1 mm in suture anchor fixation group preoperatively was significantly decreased to 2.1 mm in pullout fixation group and 2.2 mm in suture anchor fixation group postoperatively. Consequently, there were no significant differences between transtibial pullout repair and suture anchor repair in clinically and radiologically.

Jung et al. demonstrated root repair with suture anchor fixation through posterior portal and this technique showed symptomatic improvement (Lysholm score: 69.1 preoperatively, 90.3 postoperatively) in mean follow-up duration of 30.8 months [26]. Among patients checked follow-up MRI, 50% patients showed complete healing, 40% patients showed partial healing, and 10% patients showed no healing. However, mean extrusion of the midbody of the medial meniscus was 3.9 mm preoperatively and 3.5 mm postoperatively, thus, extrusion was not significantly decreased.

(c) Non-absorbable versus absorbable sutures

In biomechanical study compared biomechanical properties (cyclic loading and load to failure testing) of four different suture materials (No. 2 PDS™, No. 2 Ethibond™, No. 2 FiberWire™, 2-mm Fibertape™) for transtibial pullout repair of MMPRTs [35], PDS™ showed the lowest values for maximum load and stiffness, whereas FiberWire™ showed the highest values for maximum load and stiffness. Thus, FiberWire™ may improve healing rates and avoid progressive extrusion of the meniscus after transtibial pullout repair. However, non-absorbable suture materials can damage on meniscus tissue when pulling out the sutures under maximum force, thus, surgeon needs to be careful during fixation procedures. In second look arthroscopic examination after trasntibial pullout repair using PDS™ [34], 69.7% patients were classified into a stable healed group and 30.3% into a unhealed group. Thus, absorbable suture materials can be one of options when applying root repair.

(d) Non-locking versus locking mechanism sutures

In a biomechanical study that compared tibiofemoral contact mechanics between simple sutures and modified Mason-Allen sutures in transtibial pullout repair, the peak contact pressure and contact surface area improved significantly after fixation, regardless of the fixation method. However, repair using modified Mason-Allen sutures provided a superior contact surface area compared with that noted after fixation using simple sutures [13].

In comparative study between transtibial simple sutures repair and modified Mason-Allen sutures repair in MMPRTs, [32] clinical scores including the Lysholm score, IKDC score, and Tegner activity scores improved significantly in both groups in mean follow-up duration of 24 months. Although the clinical outcomes did not differ between the groups at final follow-up examinations, postoperative meniscus extrusion decreased 0.6 mm in the modified Mason-Allen repair group whereas extrusion increased 1 mm in the simple repair group on follow-up MRI. In terms of radiological outcomes, the modified Mason-Allen repair group did not show significant progression in the KL grade and cartilage degeneration, whereas both measures increased significantly in the simple repair group. Thus, the modified Mason-Allen repair showed more reduced meniscus extrusion and more favorable radiological outcomes [32].

2. **Clinical scores**

Clinical outcomes after root repair are shown in Table 1. Based on previous studies, root repair resulted in significant improvements in the postoperative clinical subjective scores compared with the preoperative status. Although follow-up period was extended (minimum 5-year follow-up), the postoperative clinical scores (Lysholm and IKDC subjective score) significantly improved compared to preoperative scores [7]. Thus, root repair can guarantee significantly improved clinical scores in both short-term and midterm follow-up periods.

3. **Progression of arthritis**

In Table 1, root repair did not prevent the progression of arthritis completely. In terms of KL grade progression, 5–30% patients worsened KL grade postoperatively in short-term follow-up examinations. In midterm follow-up results, 68% patients had KL grade progression postoperatively, thus, the risk of progression of arthritis seems to increase as time goes on [7]. In terms of progression of cartilage grade, 0–24% patients worsened cartilage grade postoperatively [27–32]. Problem of arthritic progression after root repair would be associated with remained meniscus extrusion and incomplete healing status postoperatively.

4. **Meniscus extrusion**

Based on meta-analysis in MMPRTs [8], meniscus extrusion was not reduced completely, although extrusion was likely to decrease postoperatively. In Table 1, studies of Kim et al. [28, 30], and Lee et al. [32] showed decreased meniscus extrusion postoperatively, whereas one study [27] showed increased postoperative extrusion.

Meniscus extrusion remained after root repair is ongoing issue in root repair. Meniscus extrusion has been shown that greater meniscus extrusion is a significant predictor of the progression of arthritic changes in osteoarthritic knees [36]. Therefore, it seems logical that if meniscus extrusion can be eliminated or reduced after root repair, the chance of subsequent degenerative arthritis will be reduced.

Chung et al. investigated the correlation between meniscus extrusion and the quality of the result after root repair (increased extrusion group versus decreased extrusion group) [21]. Transtibial pullout repair using simple stitches led to favorable midterm clinical scores, regardless of remained extrusion confirmed by 1-year follow-up MRI. However, patients with decreased meniscus extrusion at postoperative 1 year have more favorable clinical scores and radiographic findings at midterm follow-up than those with increased extrusion at 1 year (Lysholm score; 81 vs. 88, IKDC score; 71 vs. 79, percentage of KL grade progression; 87% vs. 50%, progression of joint space narrowing; 1.1 mm vs. 0.6 mm).

To get more reduced meniscus extrusion, locking mechanism sutures such as the modified Mason-Allen sutures are recommended. Because it has superior holding power and large meniscus-bone contact area that improves healing potential [22]. In a biomechanical study that compared tibiofemoral contact mechanics between simple sutures and modified Mason-Allen sutures in transtibial pullout repair, modified Mason-Allen sutures provided a superior contact surface area compared with that noted after fixation using simple sutures [13]. In comparative study between simple sutures versus modified Mason-Allen sutures repair, the modified Mason-Allen repair showed more reduced meniscus extrusion and more favorable radiological outcomes [32].

Another important considering factor to reduce meniscus extrusion is anatomic root repair with making bone bed in native root attachment area. In medial meniscus, native posterior root attachment is positioned in just lateral area of posterior cruciate ligament and just posterior area of medial eminence [3]. In patients with narrow medial compartment with tight knee, it is difficult to access native root attachment area. Surgeon can mistake to perform non-anatomic repair with making bone bed posteromedially. Non-anatomic repair can increase meniscus extrusion. In biomechanical study, non-anatomic repair did not restore the contact area or mean contact pressures compared with that of anatomic repair, whereas, the anatomic repair produced near-intact contact area and peak contact pressures compared with the intact knee [12]. Thus, anatomic root repair is a critical factor to reduce meniscus extrusion.

One of the additional procedures to help reducing meniscus extrusion is centralization technique [37–39]. Centralization technique for meniscus extrusion in which the midbody of the meniscus is centralized and stabilized onto the rim of the tibial plateau to restore and maintain the meniscus function by repairing or preventing extrusion of the meniscus. Sutures for the centralization can share the load with those for the pullout repair, so the failure risk of the pullout sutures at the torn edge can be reduced. However, centralization can present a risk to limit normal motion of the meniscus during knee extension-flexion and there is no specific report of clinical results after centralization in root repair. These are limitations of centralization technique in root repair.

Consequently, efforts to reduce meniscus extrusion during root repair can be rewarded with improved results, thus, one of the main goals of the root repair is to reduce meniscus extrusion as much as possible.

5. **Meniscus healing**

The healing condition of the repaired root is a critical factor because it is associated with postoperative meniscus extrusion status and progression of arthritis.

In MMPRTs, the surgeon can achieve complete or partial healing after root repair in almost cases (Table 1). MRI and 2nd look arthroscopy are used to confirm healing status. Among them, 2nd look arthroscopy is more reliable method to accept healing status because it can evaluate actual restoration of hoop tension, unlikely MRI. In terms of follow-up MRI results, 56.7–90.3% of complete healing, 9.7–36.7% of partial healing, and 0–6.7% of non-healing were shown postoperatively. Interestingly, 2nd look arthroscopy results would be debatable. Seo et al. [29] reported that there was no case with complete healing. Only 5 cases of lax healing (45%), 4 cases of scar tissue healing (36%), and 2 cases of non-healing (19%) were shown in 2nd look arthroscopy. However, they did not make bone bed which is essential to get bone-to-meniscus healing [29]. In contrast, Lee et al. [34] reported that 69.7% patients were classified into a stable healed group from 2nd look arthroscopy and they made a bone bed to promote healing. Lee et al. [31] reported complete healing was shown in all cases. Consequently, the surgeon can get favorable healing result after root repair by appropriate surgical technique with making the bone bed.

In lateral root radial tear, Ahn et al. [25] reported complete healing was shown in 88% patients (8/9) in 2nd look arthroscopy, although they performed concomitant ACL reconstruction and all-inside root repair using PDS™.

Healing status is connected to postoperative meniscus extrusion to prevent cartilage degeneration and progression of arthritis. Complete healing can guarantee decreased meniscus extrusion. Thus, how to improve meniscus healing and how to reduce meniscus extrusion are connected to same goal of root repair, preventing progression of arthritis.

In the next step, the surgeon should focus on how to improve biological healing. Making a large bone bed is recommended to get large bone-meniscus contact area and large amount of autologous stem cell. Additionally, biological materials with collagen matrix, such as atelocollagen, known to improve soft tissue healing can help to improve meniscus healing status [40–43].

Consequently, the healing condition of the repaired root is a critical factor to reduce meniscus extrusion and to prevent progression of arthritis. Also, the surgeon can get favorable healing result after root repair by appropriate surgical technique with making the bone bed in normal root attachment area.

6. **Mid- and long-term survivorship**

Following meniscus root repair, the mid- and long-term results are valuable because the primary aim of root repair is the prevention or delay of arthritis progression. Unfortunately, little evidence is available for assessing mid- and long-term survivorship in patients undergoing pullout repair in MMPRTs.

In a comparative study between partial meniscectomy and pullout repair in patients with MMPRTs at a minimum 5-year follow-up [7], repair group had significantly better Lysholm (84.3 vs. 62.8) and IKDC (73.7 vs. 49.3) scores than meniscectomy group. In terms of radiological results, repair group showed less KL grade progression (percentage of patients with KL grade progression; 68% vs. 100%) and less medial joint space narrowing (0.8 mm vs. 2.3 mm) than meniscectomy group. The rate of conversion to TKA was 35% in meniscectomy group, whereas there was no conversion to TKA in repair group. The 5-year survival rates in repair and meniscectomy group were 100% and 75%, respectively ($P < 0.001$).

Chung et al. [44] reported mid- to long-term survival rates in patients with pullout repair of MMPRTs. Clinical failures were defined as cases requiring conversion to TKA or having final Lysholm score <65 or less than their preoperative scores. Among 91 patients, 4 patients failed due to conversion to TKA ($n = 1$) or having final Lysholm scores <65 or less than the preoperative scores ($n = 3$) during mean follow-up duration of 84.8 months. Thus, the overall Kaplan-Meier probabilities of survival after root repair were 99% at 5 years, 98% at 6 years, 95% at 7 years, and 92% at 8 years.

Consequently, pullout repair demonstrated a high clinical survival rate in mid- and long-term follow-up examinations and it is an effective treatment to prevent or delay progression of arthritis in root tear.

7. **Prognostic factors**

Before applying root repair, identifying preoperative prognostic factors is critical to selecting the most appropriate indication and predicting postoperative results. Unfortunately, few studies reported preoperative prognostic factors in patients undergoing root repair.

In short-term follow-up results, patients with Outerbridge grade 3 or 4 chondral lesions had poorer results than those with grade 1 or 2 lesions in terms of clinical scores (American knee society score and Lysholm score) and patients with varus alignment greater than 5 degree had poorer results than those with varus alignment less than 5 in terms of clinical scores [27].

Chung et al. [45] investigated predictors of unfavorable clinical and radiologic outcomes a minimum of 5 years after pullout repair in MMPRTs. Unfavorable prognostic factors of the Lysholm score were grade 3 or 4 chondral lesions (odds ratio OR = 5.993; $P = 0.028$) and varus mechanical alignment (odds ratio = 1.644; $P = 0.017$), for IKDC scores were grade 3 or 4 chondral lesions (odds ratio = 11.146; $P = 0.038$) and older age (odds ratio = 1.200; $P = 0.017$). Preoperative higher chondral lesion (grade 3 or 4) increased the risk of KL grade progression (odds ratio = 11.000; $P = 0.031$).

Clinically, Outerbridge grade 3 or 4 chondral lesions, more varus alignment, and older age were found to predict a poor prognosis after root repair. These poor prognostic factors should be taken into consideration during surgical decision making. If the patients with those factors need root repair, the possibility of poor outcomes should be discussed when obtaining informed consent.

Conclusions

Meniscus root tears completely disrupt the continuity of the circumferential fibers, leading to loss of hoop tension, loss load sharing ability, and unacceptable peak pressures. This series of processes leads to degenerative arthritic changes. However, meniscus root repair restores the hoop tension of the medial meniscus and its ability to dissipate forces, which can slow the progression of arthritis in most cases. Encouraging results from root repair over the last decade have increased interest in this procedure. Therefore, a recent international consensus statement has emphasized the effectiveness of repair of meniscal root instead of meniscectomy or conservative treatments. Even in mid- and long-term follow-up examinations, transtibial pullout repair demonstrated a high clinical survival rate and the patients demonstrated clinical improvement.

Still now, the critical problem of root repair is a limited efficacy in complete prevention of arthritic changes, although it slows down the arthritic changes. There are several challenges to overcome, especially how to get complete healing, how to get complete reduction of meniscus extrusion, how to manage concomitant cartilage problem, and which degree of mechanical alignment is acceptable to achieve favorable outcome. In facing those challenges, we will continue to improve our surgical and perioperative management to repair root tears, to save the meniscus, and ultimately to restore the normal knee function.

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Meniscus Allograft Transplantation—Basic Principle

Seong-Il Bin

Abstract

Meniscal allograft transplantation (MAT) is an effective treatment for patients with symptomatic meniscus-deficient knee after total or subtotal meniscectomy. Since Milachowski performed the first MAT in 1984, there have been many advances in indications, graft selection, and surgical techniques over 30 years and satisfactory long-term clinical results have been reported. Therefore, MAT is now no longer considered an experimental procedure. Thus, it is important to understand indications, surgical techniques, results, and complications of MAT to achieve successful long-term joint preservation in young patients.

Keywords

Meniscus · Allograft · Transplantation

Introduction

The meniscus has important functions in the knee joint, including shock absorption, load transmission, lubrication, joint stabilization, and proprioception [1–5]. Meniscal injuries are common knee injuries. The treatment principle of meniscal tears is to preserve as much of the meniscus as possible using partial meniscectomy or repair. However, despite every attempt being made to preserve the meniscus, meniscal repair or partial meniscectomy is not always possible, and subtotal/total meniscectomy is inevitable in some cases. After subtotal or total meniscectomy, meniscus will lose its functions, subsequently leading to arthritic changes in the knee joint. The natural history of a meniscus-deficient knee has proved to result in poor outcomes over time due to changes in the biomechanical environment of the knee, potentially leading to subsequent degenerative wear of the articular cartilage [6].

The goal of meniscal allograft transplantation (MAT) is restoring the biomechanics in meniscus-deficient knees. The MAT has been reported to provide pain relief and improves knee joint function in active and young patients [7, 8]. The number of patients undergoing MAT is increasing, and satisfactory long-term clinical outcomes have been reported [9].

Biomechanics

Native menisci are fibrocartilaginous structures inside the tibiofemoral joint. They are crescent-shaped in the axial plane and wedge-shaped in the coronal and sagittal planes. Their unique and

S.-I. Bin (✉)
Department of Orthopedic Surgery, Asan Medical Center, University of Ulsan College of Medicine, Seoul 05505, Republic of Korea
e-mail: sibin@amc.seoul.kr

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highly complex structure and material property of the meniscus can provide important functions in the knee joint. Native menisci consist of roughly 75% water, 20% type 1 collagen, and 5% other materials [10]. Overall, the collagen fiber forms a dense framework that consists of radial and circumferential fibers [11]. Radial collagen fibers hold bundles of circumferential fibers together; thus, on axial loading, compressive forces produce hoop stresses that distribute the load throughout the tibiofemoral joint, which is the primary role of the meniscus.

To see the gross structure of the knee joint, the femoral side is convex and the tibial plateau is slightly concave in the medial compartment and convex in the lateral compartment. Without the meniscus, the articulation of the tibia and femur cannot be congruent. However, the upper surface of the meniscus is concave and fits the convex femoral side, while the lower surface of the meniscus is flat and fits the tibial plateau. It increases the congruency of the tibiofemoral joint, providing effective load transmission. The medial meniscus is C-shaped, covering 60% of the tibial plateau of the medial compartment. On the other hand, the lateral meniscus is more round in shape and covers 80% of the tibial plateau. The medial compartment consists of a convex femoral surface and a concave tibial surface. The medial meniscus transmits approximately 50% of the load. The lateral compartment consists of a convex femoral surface and a relatively convex tibial surface. The lateral meniscus transmits approximately 70% of the load [12]. Therefore, the effect of meniscal loss is more evident in the lateral compartment than in the medial compartment due to anatomical characteristics of condyle shape and load-bearing property of meniscus [13, 14].

The meniscus also provides stability to the knee joint. This is particularly important for the medial meniscus due to its location in the posterior horn, which buttresses against the anterior translation of the tibia [15]. So in case of anterior cruciate ligament(ACL) tear, injury of medial meniscus posterior horn will increase anterior instability.

Loss of meniscus leads to reduced congruency of the tibiofemoral joint, resulting in decreased contact area, increased peak contact

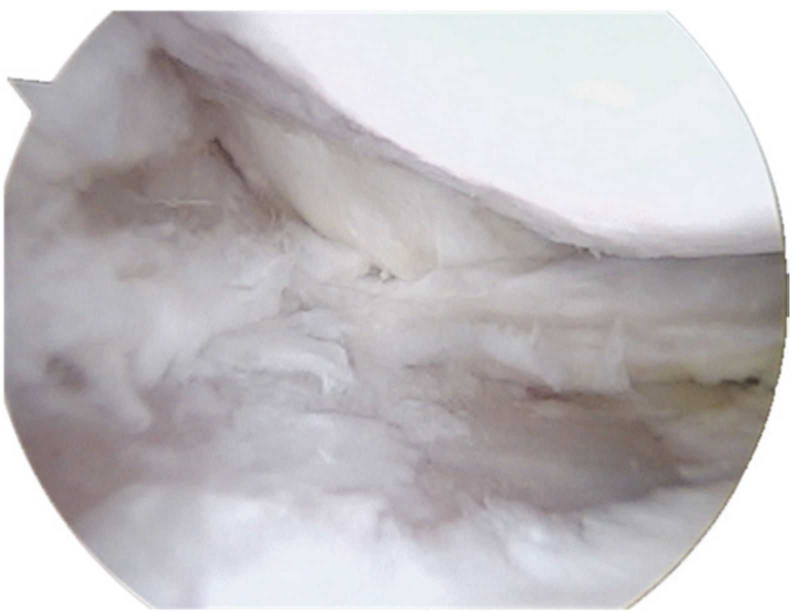

Fig. 1 Arthroscopic image of a 30-year-old male patient who underwent total lateral meniscectomy for tear of discoid lateral meniscus at the age of 20. Arthroscopic exam showed advanced degeneration and loss of cartilage in the lateral compartment

pressure, and compressive and shear forces on the articular surface, eventually leading to early cartilage degeneration [6] (Fig. 1).

Indication

Appropriate patient selection according to proper indications is essential for obtaining acceptable clinical results of MAT. Indications for meniscal transplantation are evolving as long-term clinical results have been available. However, currently accepted ideal indications of MAT, based on previous studies, are as follows: (1) physically active patients < 50 years old; (2) persistent affected knee compartment pain or swelling attributed to meniscus-deficiency after prior total or subtotal meniscectomy; (3) intact articular cartilage (Outerbridge grade ≤ II); (4) normal alignment of the mechanical axis; and (5) knee stability [7, 16, 17].

Studies have shown good clinical outcomes when the above ideal surgical indications are matched [18]. It is necessary to evaluate patients using a comprehensive approach. The symptoms of patients should be addressed in detail, including whether pain or swelling is induced upon the usual daily activity or heavy work and whether it comes from the affected compartment. Preoperative physical examination should include evaluation of ligament function. At least 2 mm of preserved joint space width on standing anteroposterior knee radiographs and 45° flexion posteroanterior knee radiographs (Rosenberg view) must be confirmed prior to the consideration of MAT. Alignment of the lower extremities should be determined on long-standing hip-knee-ankle plain radiographs. High-resolution magnetic resonance imaging (MRI) is helpful to evaluate articular cartilage status and other combined knee pathologies.

To consider the effect of MAT on load distribution, young and active patients with meniscus-deficient knees in whom cartilage degeneration is expected would benefit from MAT with the aim of preventing or slowing the osteoarthritis process and at least delaying symptom onset. However, the chondroprotective effect of MAT remains controversial, and considering its risks and benefits, routine prophylactic MAT in asymptomatic patients is not recommended at this time point.

Although MAT in asymptomatic patients is not routinely recommended, it is important to pay attention to the cartilage status of meniscus-deficient knee, and regular follow-up is recommended. Symptoms of the patient and cartilage status of the knee joint are not correlated in some cases. It should be kept in mind that preoperative symptom severity does not reflect articular cartilage status. Mild or tolerable symptoms do not indicate well-preserved articular cartilage [19]. Thus, radiologic evaluation to confirm the articular cartilage status is important in asymptomatic patients. A regular check-up should be needed to find the signs of potential joint degeneration.

The acceptable degree of chondral wear for MAT is controversial. MAT was not traditionally indicated in patients with high-grade chondral wear (Outerbridge grades III and IV) [20, 21]. But some recent studies have reported favorable clinical outcomes in terms of symptom improvement in patients with high-grade chondral wear treated with MAT and concurrent cartilage procedures such as microfracture, osteochondral autograft transfer, osteochondral allograft transplantation, or autologous chondrocyte implantation [22, 23]. Even though symptom is improved, worse survivorship can be expected in patients with high-grade chondral wear [24]. Thus, in selective young patients with arthritic changes in whom conservative treatment has failed and no other surgical options exist, MAT can be considered with caution as a salvage procedure.

Any malalignment and ligament instability should be corrected before or at the time of MAT. Recent clinical studies have shown that this combined surgery may be able to improve clinical outcomes and obtain results as good as the results of isolated MAT [25]. In a recent systematic review, over half of all the patients who underwent MAT also underwent at least one other concurrent procedure (45% cartilage procedures, 37% ACL reconstruction, and 13% osteotomy) [17].

MAT in a malaligned knee will cause excessive loading on allograft and results in poor graft survival and clinical outcomes. Lateral MAT should not be considered in a valgus aligned knee, while medial MAT should not be considered in a varus aligned knee. In case of malalignment, it is important to restore the mechanical axis to neutral alignment with prior or concomitant osteotomy. The range of acceptable alignment and amount of correction are controversial. When the weight-bearing line falls into the affected compartment, it is considered as malaligned knee in most studies, and correction to neutral alignment or even minimal overcorrection is recommended. Van Thiel et al. [26] observed that 3° valgus correction of a neutrally aligned knee with concurrent medial MAT can significantly decrease peak and total medial compartment contact pressures. This effect was observed without a corresponding increase in peak pressure in the lateral compartment. A long-term clinical study is needed to address the additional effects of realignment osteotomy on joint survival.

Ligament instability of the knee joint should be corrected prior to or concomitantly with MAT, particularly in cases of medial MAT with ACL deficiency. ACL and medial meniscus have a complementary effect on anteroposterior stability of the knee joint. Medial meniscus is an important secondary stabilizer of the knee to anterior tibial translation in an ACL-deficient knee. ACL reconstruction is expected to positively affect medial MAT.

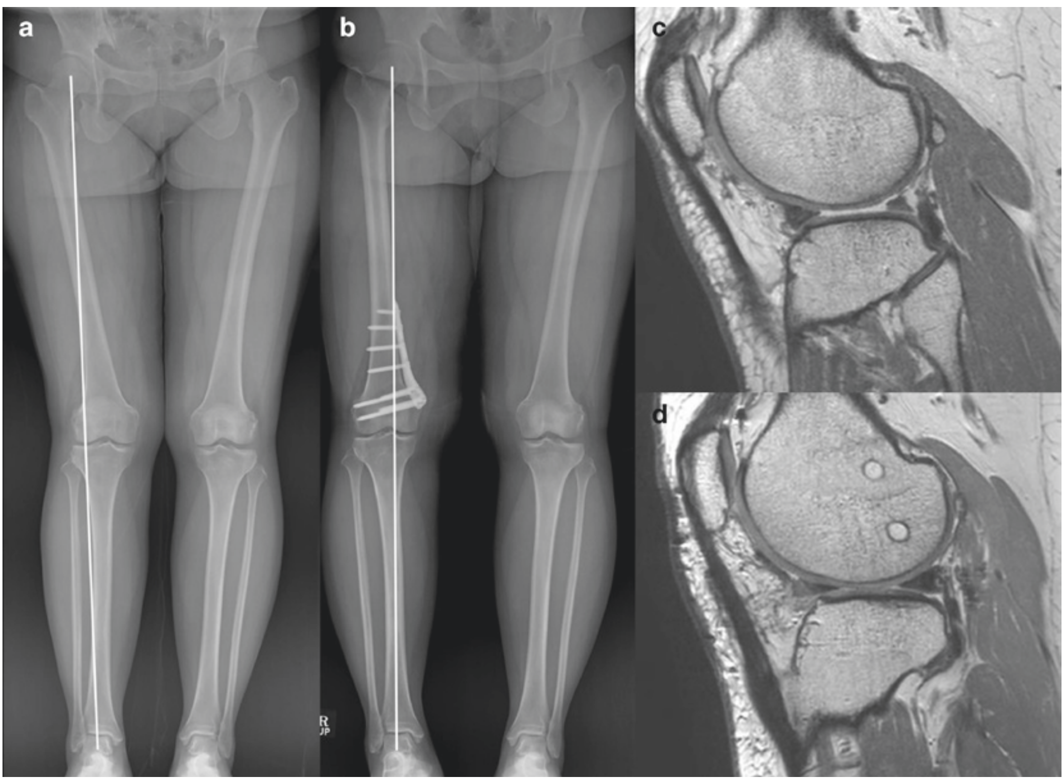

Fig. 2 Preoperative and Postoperative long-standing hip-knee-ankle (HKA) radiographs and magnetic resonance imaging (MRI) scans of a 45-year-old female patient who underwent right lateral meniscal allograft transplantation. **a** Preoperative long-standing HKA radiograph showed valgus alignment of the right lower extremity, and the weight-bearing line fell into the lateral compartment. **b** Closed wedge distal femoral osteotomy was performed to correct alignment prior to lateral meniscal allograft transplantation. **c** Coronal image of preoperative MRI scan showed lateral meniscus-deficiency of right knee joint. **d** Lateral meniscal allograft was performed with key-hole technique

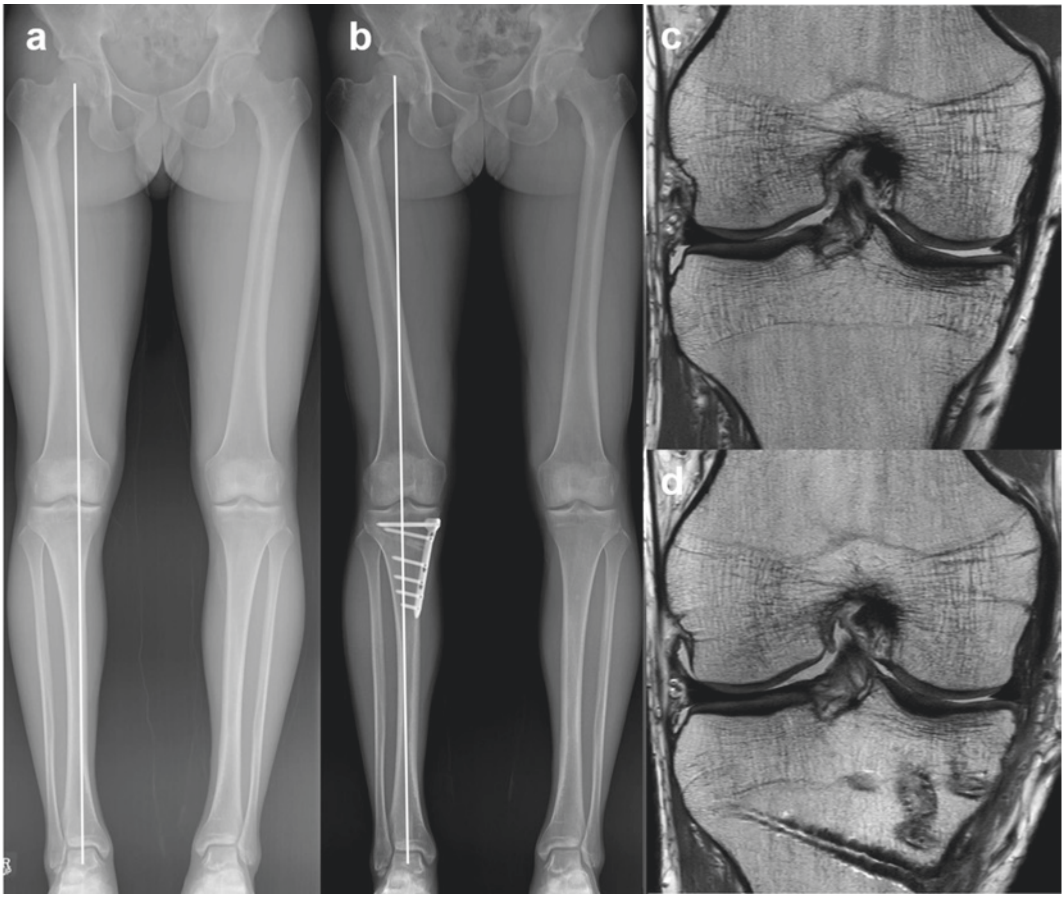

Fig. 3 Pre- and Postoperative long-standing hip-knee-ankle (HKA) radiographs and magnetic resonance imaging (MRI) scans of a 27-year-old male patient who underwent right medial meniscal allograft transplantation. **a** Preoperative long-standing HKA radiograph showed varus alignment of right lower extremity, and the weight-bearing line fell into the medial compartment. **b** Open wedge high tibial osteotomy was performed to correct alignment prior to medial meniscal allograft transplantation. **c** Coronal image of preoperative MRI scan showed medial meniscus-deficiency of right knee joint. **d** Transplanted medial meniscal allograft was well positioned without extrusion

Although the upper age limit for MAT is usually 50–55 years, [7] age on its own should not be an absolute contraindication. Even in patients around 50, MAT may be considered as potential candidates according to the demand of patients, activity level, alignment, and cartilage status.

The absolute contraindications to MAT include (1) inflammatory arthritis, (2) previous infection of the knee joint, and (3) skeletal immaturity [27, 28] (Figs. 2 and 3).

Graft Sizing

To restore the biomechanics of a meniscus-deficient knee, it is important to match an appropriate allograft with proper preoperative evaluation. An oversized allograft will not provide enough load distribution, while an undersized allograft will be exposed to excessive loading and may eventually lead to early graft failure. Although few studies have focused on the consequences of size mismatch, a 5–10% size difference appears to be well tolerated [29]. Nevertheless, it is advisable to oversize rather than to undersize an allograft since the former can be partially addressed and surgically adjusted. There are several methods for determining the recipient meniscal size, including plain radiography with calibration, computed tomography, MRI, and recipient anthropometric data. The method using calibrated plain anteroposterior and lateral plain radiographs as proposed by Pollard et al. is the most widely used. To ensure precise measurements using the Pollard method, it is important to obtain a true anteroposterior radiograph with the patella facing forward and a true lateral radiograph. According to this method, meniscal width is estimated in the anteroposterior view by measuring the distance between the peak tibial eminence and the metaphyseal margin of each compartment. Meniscal length is estimated by tibial plateau length, which is the distance between two vertical lines tangential to the anterior and posterior margin of the tibial plateau at the articular level. The length of medial meniscus is estimated as 80% of the measured tibial plateau length, while lateral meniscus length is estimated as 70% of the measured tibial plateau length on a true lateral radiograph [30]. For lateral meniscal allografts, measurements using this method may be less accurate [31]. Computed tomography can provide more accurate measurements but involves higher cost and radiation exposure. Measurements using ipsilateral or contralateral MRI have been introduced and can provide more geometrically precise measurements for determining meniscal allograft length [32, 33]. In this method, allograft width is the distance from the meniscocapsular junction to the tibial spine in the mid-coronal view and allograft length is the distance between the most anterior portion and the most posterior portion in the mid-sagittal view. In case of a severely extruded capsule or residual meniscal rim, although costly, MRI of the contralateral knee may be useful for determining the size of meniscus, but possible side difference should be considered. Besides these methods, mathematical formulae using patients' preoperative anthropometric data including sex, weight, and height can be used [34] (Fig. 4).

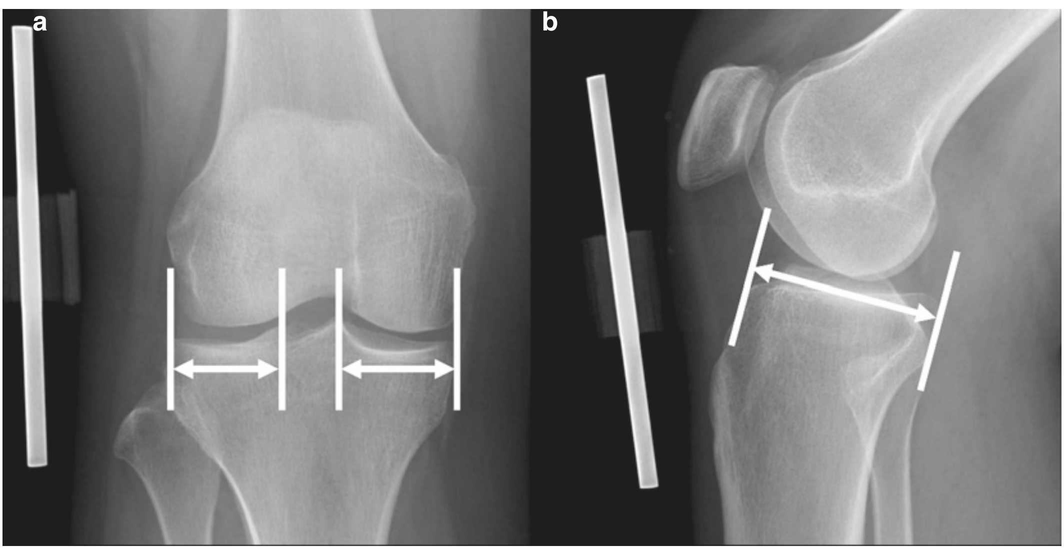

Fig. 4 Pollard method. **a** An anteroposterior radiograph of the knee. The meniscal width is estimated in the anteroposterior view by measuring the distance between the peak tibial eminence and the metaphyseal margin of each compartment (white arrow). **b** Meniscal length is estimated by tibial plateau length (white arrow), which is the distance between two vertical lines tangential to the anterior and posterior margin of the tibial plateau at the articular level. The length of medial meniscus is estimated as 80% of the measured tibial plateau length, while lateral meniscus length is estimated as 70% of the measured tibial plateau length on a true lateral radiograph

Graft Selection

The choice of allograft can have a potentially significant impact on outcome and survival. The meniscus is mainly an acellular structure consisting of avascular tissue except for the peripheral third. Most of the meniscal function is derived from extracellular matrix structure. Thus, the ideal allograft preservation technique should maintain the mechanical properties of the meniscus and be simple to process and store. Currently, there are four preservation methods: lyophilization (freeze-drying), viable (fresh), deep-frozen (fresh-frozen), and cryopreservation.

The lyophilization technique consists of drying the harvested meniscus under a vacuum and freezing condition to allow unlimited storage. However, this method alters the mechanical properties of the allograft, and the clinical results of their use have shown high failure rates with severe allograft shrinkage [35]. This method also requires 2.5 mrad of gamma irradiation for sterilization, which may be detrimental to the tissue over time, leading to reduced tensile strength and graft shrinkage [36]. Thus, its use is no longer recommended for processing meniscal allografts [37].

The deep-frozen (fresh-frozen) technique involves soaking the harvested meniscus in a sterile antibiotic solution and rapidly freezing it to −80 °C [38]. These allografts are thawed just before surgery at room temperature in normal saline solution with antibiotics. This method is technically simple, and the grafts are easy to store and remain stable for up to 5 years. They also have very low immunogenicity and a low risk of disease transmission. Although donor cells may be destroyed by the freezing process, the lack of cell viability has not been shown to adversely affect graft survival or clinical outcomes. Currently, fresh-frozen nonirradiated allografts are most commonly used, featuring excellent mid- to long-term survival without significant deterioration of meniscal properties.

Cryopreservation involves progressive freezing of the graft at −1°/min until −196 °C in a cryoprotectant to protect cell viability by preventing the formation of intracellular ice crystals [39]. Although this method might maintain cell viability and the collagen ultrastructure of the meniscus, recent studies have suggested that only 4–54% of cells actually survive, [40] and it does not offer significant benefits over fresh-frozen allografts due to its high cost and difficult processing.

The primary advantage of fresh or viable allografts is that they preserve viable fibrochondrocytes, which produce the extracellular matrix. Although clinical outcomes are good with excellent survival, there are some issues, including harvest timing, proper recipient matching, higher risk of transmission, and high cost. There is an obvious logistic problem of correctly matching a recipient donor before the fibrochondrocyte cellularity diminishes and graft viability is lost. For this reason, implantation should occur within 14 days of harvest [37, 41]. Practically, it can be difficult to transplant fresh allografts into appropriately matched recipients [42].

Except for lyophilization grafts, no proven definite clinical superiority of MAT has been shown. However, the aforementioned advantages of fresh-frozen nonirradiated allografts, such as the convenience of storage, cost-effectiveness, and lower risk of disease transmission, are increasing their popularity and wide use.

Parameter	Lyophilization	Cryopreserved	Fresh-Frozen	Viable
Viable cells	Acellular	Yes	Acellular	Yes
Preservation methods	Vacuum freezing	Controlled freezing process	Stored at −80 °C	Ringer's lactate solution at 4 °C
Storage duration	Indefinite	10 years	Up to 5 years	14 days
Risk of disease transmission	Low	Potentially exists	Low	Potentially high
Advantages	Low cost	Main collagen framework maintained	Low cost	Donor cell preservation; minimal disruption of meniscal integrity

Surgical Technique

Various surgical techniques have been introduced, which can be classified into two main fixation techniques: soft tissue fixation and bone fixation. Although there is no proven clinical superiority between these two fixation categories, the latter is associated with slightly superior biomechanical properties and fewer postoperative complications and is more widely used [43, 44]. Specific surgical techniques for MAT will be described in the next chapter.

Outcomes

The primary purpose of MAT is to relieve pain and improve function in patients with meniscus-deficient knees to ensure long-term joint survival. Several systematic reviews have shown a consistent improvement of clinical outcomes in terms of symptoms and function after MAT [7, 17]. Smith et al. [7] reported systematic review of patient-reported outcomes in 35 studies including 1332 patients and 1374 knees undergoing MAT with a mean follow-up of 5.1 years. Across all studies, Lysholm scores improved from 55.7 to 81.3, IKDC scores from 47.0 to 70.0, and Tegner activity scores from 3.1 to 4.7 between preoperative and final follow-up assessments, respectively. The mean failure rate across all studies was 10.6% at 4.8 years, and complication rate was 13.9% at 4.7 years. Another systematic review of 55 studies with weighted average follow-up of 53.61 months showed that MAT provides good clinical results at short-term and mid-term follow-up with improvement in knee function. The weight average Lysholm score increased from 55.5 preoperatively to 82.7 at the last follow-up. Similarly, the weighted average overall VAS score for pain decreased from 6.4 to 2.4 at the last follow-up. However, the clinical outcome score tended to decrease over time [17].

In most studies, MAT outcomes were evaluated using clinical parameters such as Lysholm score, International Knee Documentation Committee score, and visual analog scale score [8, 18, 45]. Therefore, the proven benefits of the procedure are pain relief and functional improvement. Because MAT is a procedure for active young patients with symptomatic knee after meniscectomy, patient-reported outcome, pain, and activity scores should be considered as primary outcomes of the operation. However, these clinical assessments do not accurately reflect the status of meniscal transplants. It is more worthwhile to thoroughly assess the graft condition and joint preservation effect in objective evaluation studies with a high level of evidence. Arthroscopy is the most accurate objective evaluation method, but it is an invasive modality. Thus, MRI scans are more commonly used as a relatively reliable and noninvasive evaluation method [46].

Recent short- or mid-term objective evaluation studies provide more favorable results than past studies in the literature. Ha et al. [47] performed second-look arthroscopy at a minimum of 2 years after medial MAT in 11 of 22 patients, which revealed complete healing in more than 80% of patients and cartilage degeneration in 4 patients (36.4%). Kim et al. [48] confirmed on MRI or second-look arthroscopy that the allografts were satisfactory in 20 patients (69.0%) and fair in 5 (17.2%) at a minimum of 2 years after 29 cases of isolated lateral MAT. In a study by Marcacci et al. [49], pain relief and functional improvement were achieved in 94% of 32 patients at a mean of 40 months after MAT, while MRI showed an improved cartilage condition on the femoral side and tibial side at a mean of 36 months postoperatively. Kim et al. [50] reported the objective evaluation results of MAT using bone fixation. Of the 115 patients, 110 (95.7%) knees were followed up for more than 2 years, and MRI or second-look arthroscopy was performed in all 110 cases. The clinical improvement was achieved in 104 of the 110 knees (94.5%). Classification by clinical outcome, MRI and second-look arthroscopy was graded as satisfactory in 90 (81.8%), fair in 8 (7.3%), and poor in 12 (10.9%) patients.

Since Milachowski et al. first performed MAT with ACL reconstruction in 1984, [51] several long-term follow-up results have been reported. However, early MAT cases showed less optimal results as early MAT was experimental in terms of indications, surgical techniques, and graft selections. Wirth and Milachowski et al. [52] evaluated the clinical outcome of MAT in 23 cases consisting of 22 cases with 17 lyophilized grafts and 6 deep-frozen graft at 3 years and 14 years postoperatively. The overall results were satisfactory although the Lysholm score decreased from 84 points at 3 years postoperatively to 75 points at 14 years postoperatively. The clinical results were better in the deep-frozen graft group than the lyophilized graft group. The lyophilized graft showed severe shrinkage of allograft on magnetic resonance imaging (MRI) and second-look arthroscopy. In another long-term report by Binnet et al. [35], all of the 4 patients had grade 4 degenerative arthritis at 19 years after lyophilized graft transplantation combined with revision ACL reconstruction. The long-term result of early MAT cases with lyophilized grafts was associated with high graft failure due to severe shrinkage of allograft. Thus, lyophilized graft is no longer recommended for MAT.

However, some recently reported long-term follow-up studies demonstrated more favorable results. Hommen et al. [53] reported the results of MAT using cryopreserved allograft with a follow-up of 10 years. The overall improvement in Lysholm score and pain occurred in 90% of patients. Sixty-six percent of cases available for MRI showed joint space narrowing and 80% progression to degenerative joint disease. The 10-year survival rate of the allografts based on the clinical outcome and objective evaluation results was 45% (9 of 20 patients). Van der Wal et al. [54] assessed the results of 63 open meniscal transplantation procedures using a cryopreserved graft at a mean of 13.8 years postoperatively. They suggested that the procedure would be a good salvage option with an overall failure rate of 29% in the meniscectomized knee despite functional deterioration (Lysholm score, 61 points) at the last follow-up. Vundelinckx et al. [55] reported long-term survival analysis of 50 MATs with a mean follow-up of 12.7 years (112–216 months). The failure was defined as 2 events: conversion to TKA and any operative reintervention. When the failure was defined as conversion to TKA, the 10-year survival rate was 90.3% and the 15-year survival rate was 74.7%. When the failure was defined as any kind of operative reintervention, the 10-year survival rate was 62.6% and the 15-year survival rate was 59.1%. Noyes et al. [56] reported the long-term function and survival rates of 69 of 72 consecutive medial and lateral MATs. In this study, survival endpoint were reoperation, MRI failure (grade 3 signal intensity, extrusion > 50% of meniscal width), meniscal tear on examination, and radiologic loss of joint space width. For all transplants, the estimated probability of survival was 85% at 2 years, 77% at 5 years, 69% at 7 years, 45% at 10 years, and 19% at 15 years. In that study, 21 transplants were rated as failed according to MRI or radiographic criteria; however, 16 of these patients rated their knee condition as good to normal a mean of 13.1 ± 3.1 years postoperatively. Kim et al. [57] reported long-term survival analysis of 49 MATs with bone fixation. The failure was defined as (1) subtotal resection of the allograft, (2) conversion to total knee arthroplasty, or (3) a modified Lysholm score less than 65 or that of the preoperative status. There were 2 failures noted at 6 months and 11.3 years, respectively, during the mean follow-up period of 11.5 years. The 10-year survival rate was 98.0% and the 15-year survival rate was 93.3%.

The chondroprotective effect of MAT is still controversial. Some biomechanical studies reported the chondroprotective effect of MAT, as they have shown that meniscal transplantation improves peak contact stresses and total contact area after meniscectomy [58–60]. One study found that peak contact stresses were not significantly different in either the native or the transplanted knee [61]. Animal model studies have also demonstrated chondroprotective effects of meniscal allograft transplantation when compared with meniscectomy. Furthermore, in a systematic review looking at radiologic joint space narrowing after MAT, Smith et al. [18] observed 0.032 mm of joint space narrowing at a mean follow-up of 4.5 years, which is less than what

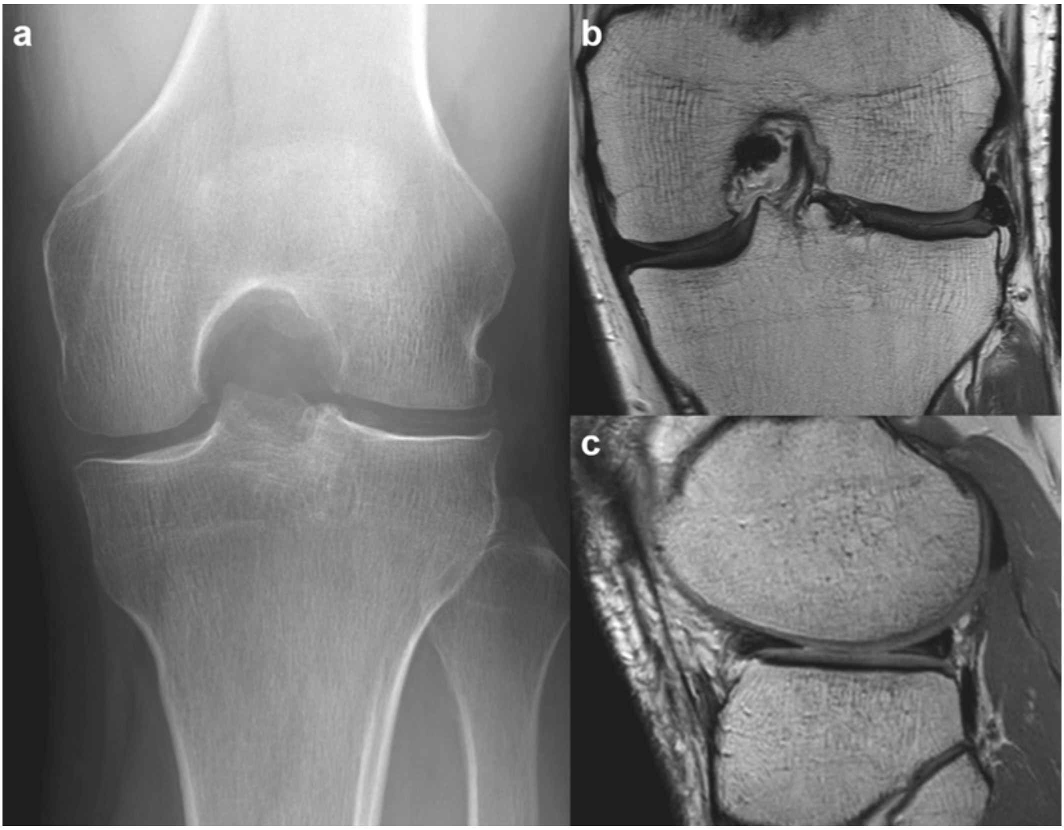

Fig. 5 Magnetic resonance imaging (MRI) scans and 45° flexion posteroanterior views of the left knee joint of a 38-year-old male patient who underwent lateral meniscus meniscal allograft transplantation at age of 18. **a** Joint space width is well preserved with minimal spur on margin of lateral tibial plateau. **b**, **c** Coronal and sagittal image of MRI scan at postoperative 20 years showed well-preserved allograft and intact cartilage

would be expected in an OA control population. This represents weak evidence to support the hypothesis that MAT may reduce the progression of OA, yet still does not support the use of MAT as a prophylactic procedure to prevent OA. Lee et al. [62] reported reduced progression in radiologic arthrosis after lateral MAT. In that study, patients who underwent isolated lateral MAT showed substantial articular cartilage degeneration at the time of initial subtotal/total lateral meniscectomy, and this degeneration progressed thereafter. However, further progression of radiographic arthrosis was delayed after lateral MAT.

Despite these results, it is difficult to draw definitive conclusions without high-level evidence studies such as prospective controlled trials. The chondroprotective effect of MAT remains elusive (Fig. 5).

Rehabilitation

A few comparative studies on rehabilitation protocols after MAT have been published, and standard rehabilitation protocols are lacking. However, they generally follow similar or stricter protocols than meniscal repair procedures. They can also be adjusted or modified according to individual factors, such as preoperative activity level, muscle strength, and combined knee pathologies or procedures. The general rehabilitation protocol consists of four stages.

In the first stage (early protection phase: 0–3 weeks), in the first 3 weeks after MAT, passive range of motion of the knee joint of 0–60° is allowed to minimize movement of the transplanted meniscal allograft. It is important to achieve full extension of the knee if possible. Icing to diminish swelling and analgesics to control pain are required. Quadriceps strengthening with isometric exercise, including straight leg raising, is encouraged. Protective weight-bearing, 10–20% of weight-bearing with 2 crutches, is allowed.

In the second stage (restoration phase: 3–6 weeks), after the first 3–4 weeks, 90° of knee flexion is allowed until 4 weeks, while 120° is allowed until 6 weeks. Progressive weight-bearing is allowed. If knee flexion up to 120° is possible, stationary bicycle exercise is encouraged.

In the third stage (strengthening and conditioning phase: 6 weeks–3 months), at 6–8 weeks after surgery, full weight-bearing is allowed, and full range of motion should be achieved. Isokinetic exercise as well as progressive open and closed chain exercises with mild resistance can be started.

In the fourth stage (functional rehabilitation phase: 3–6 months), at 6 months after surgery, extensor and flexor muscle power should be evaluated using isokinetic muscle strength testing, and efforts to minimize the difference in muscle power and restore bilateral leg balance are required.

In several studies on the ability to return to high-impact sports after MAT, they reported that 74% of patients were able to return to sports after a minimum rehabilitation period of 8 months. Half of the patients returned to the same preinjury level. A similar return to the preinjury level was reported in other studies [63–65]. However, long-term clinical results after returning to high-level sports are not well documented since the main purpose of MAT is long-term joint survival. Generally speaking, high-impact sports are not recommended. For long-term joint survival, athletic activity should be limited to light sports. It is imperative that patients be made aware of such limitations prior to surgery.

Conclusions

MAT is a useful treatment method to achieve functional improvement and symptomatic relief in symptomatic patients with meniscus-deficiency. It has been established in mid- and long-term studies that MAT is effective for reducing pain and swelling and improving knee function. A personalized and goal-oriented approach is required that recognizes that the main purpose of MAT is achieving long-term joint survival in young patients.

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Delayed Rehabilitation After Meniscal Allograft Transplantation

Dhong Won Lee, Jae Il Lee and Jin Goo Kim

Abstract

Graft extrusion after meniscal allograft transplantation (MAT) has been reported to be a distinct feature of transplanted meniscus and has not been resolved. Biomechanically, insufficient articular cartilage coverage generated by graft extrusion leads to failure in normal biomechanics of knee joint. Causes of the graft extrusion are uncertain, but there are possible explanations such as preoperative size measurement error, geometrically unmatched graft, mal-positioned graft, over-tensioning of the graft suture, or soft tissue contracture at the meniscocapsular junction. However, literature on the rehabilitation strategy to reduce meniscal graft extrusion is lacking. Our delayed rehabilitation program aims to restrict the initial range of motion and minimize the load on the graft up to three months after MAT. We suggest that this delayed rehabilitation can provide a positive effect on mechanical stabilization and biological healing of the graft protecting the healing process at the relatively weak meniscocapsular attachment.

Keywords

Meniscus · Meniscal allograft transplantation · Extrusion · Magnetic resonance imaging · Rehabilitation

Introduction

Meniscal allograft transplantation (MAT) has been shown to improve knee pain and function, and to have some effect on delaying the progression of cartilage degeneration, even though further prospective trials are needed. [1–5] Recent systematic review reported by Novaretti and colleagues [6] concluded that MAT can yield good long-term survivorship rates, with 73.5% and 60.3% after 10 and 15 years, respectively.

In evaluating the results after the MAT, most studies have used subjective clinical scores such as Lysholm score, International Knee Documentation Committee (IKDC) subjective score, and visual analog scale (VAS). However, these subjective evaluation tools alone do not accurately reflect the real condition of the MAT. Radial displacement of the meniscal graft is a commonly evaluated radiological complication

D. W. Lee (✉) · J. I. Lee
Department of Orthopaedic Surgery, Konkuk University Medical Center, Konkuk University School of Medicine, Seoul, Republic of Korea
e-mail: osdoctorknee@kuh.ac.kr

J. I. Lee
e-mail: Jil1223@naver.com

J. G. Kim
Department of Orthopaedic Surgery, Hanyang University Myongji Hospital, Gyeonggi-do, Republic of Korea
e-mail: boram107@daum.net

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following the MAT. Radial displacement of the meniscus, namely as meniscal extrusion, is related to its dysfunction, because the radiological signs of this condition are similar to those of meniscectomized state. [7–9] Graft extrusion is measured from the distance of the superolateral or superomedial aspect of the tibial plateau to the peripheral margin of the graft at the level of the mid-coronal plane on magnetic resonance imaging (MRI), and pathologic extrusion is usually defined as graft extrusion > 3 mm (Fig. 1). [10–15] Recent meta-analysis reported that mean graft extrusion after MAT using bony fixation was 3.2 mm, and major graft extrusion > 3 mm was occurred in about 50% of MATs. [16].

As the graft extrusion has been one of the various criteria of graft failure such as graft removal, conversion to total knee arthroplasty, or persistent pain, reducing the degree of graft extrusion can be a way to decrease the failure rate of MAT. Biomechanically, insufficient articular cartilage coverage generated by graft extrusion leads to failure in shock absorption and load distribution. [1, 5, 17–20] Lee and colleagues [21] revealed that long-term follow-up (a minimum 8-year follow-up period) after MAT showed a greater decrease in joint space width in the extrusion group (n = 19) than in the non-extrusion group (n = 26) (p = 0.017). Causes of the graft extrusion are uncertain, but there have been possible explanations such as preoperative size measurement error, geometrically unmatched graft, mal-positioned graft, overtensioning of the graft suture, soft tissue contracture at the meniscocapsular junction, or osteophytes. [15, 22–24] In this sense, there have been efforts to minimize graft extrusion, although the clinical relevance of graft extrusion after MAT remains unclear. There have been several literature of surgical techniques to prevent graft extrusion: graft size reduction; anatomic placement of the anterior and posterior horns; peripheral osteophyte excision; and joint capsule stabilization. [14, 22–27]

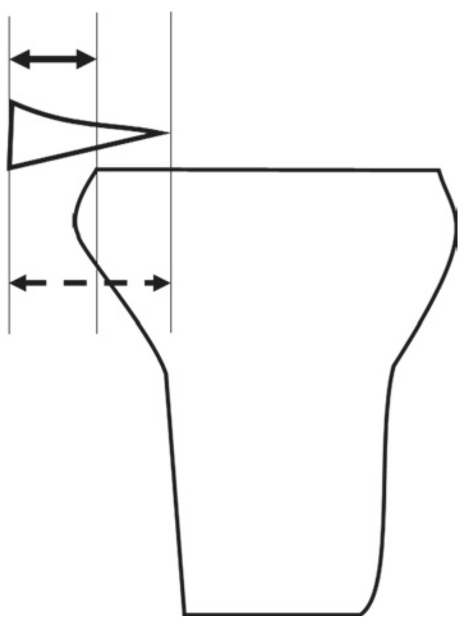

Fig. 1 Absolute graft extrusion is measured from the distance (two-sided arrow) of the superolateral aspect of the tibial plateau to the peripheral margin of the graft. Relative percentage of extrusion is defined as the percentage of the width of extruded graft (two-sided arrow) relative to the entire graft width (dotted two-sided arrow). The pathologic graft extrusion is defined as absolute graft extrusion > 3 mm

In this chapter, we are going to discuss the rehabilitation strategy to minimize graft extrusion that has not been covered much before.

Conventional Rehabilitation

Range of Motion (ROM)

In previous studies, most authors recommend early ROM exercises after the MAT. Rath and colleagues [28] recommended that immediate ROM exercise be carried out within a range of 0 to 90 degrees for four weeks at the beginning of the day after the surgery. Kim and colleagues [29] started a continuous passive range of motion exercise at 2 days after MAT, and limited flexion of the knee within 90 degrees until 4 weeks postoperatively. They encouraged knee flexion angles to 120 degrees starting at 4 weeks and continuing until 6 to 8 weeks postoperatively. [29] Verdonk and colleagues [30] presented that ROM exercise be performed in the early stage within a range of 0 to 60 degrees for 3 weeks after the surgery. Kim and colleagues [31] similarly recommended that the goals were to achieve 90 degrees of flexion within 3 weeks and 120 degrees of flexion at 6 to 8 weeks.

Weight-Bearing

There has been a general consensus throughout the literature that full weight-bearing can be achieved at six weeks postoperative after a period of limited weight-bearing. [32] Literature review by Rijk [33] recommended that restricted weight-bearing for 4 ~ 6 weeks after the MAT is performed to stabilize graft fixation and to preserve healing potential while the revascularization of meniscal graft occurs. In a mean 12.3-year follow-up study after the MAT performed by Lee and colleagues [21], weight-bearing gradually transitioned from toe-touch only during the first two weeks to full weight-bearing at 6 ~ 8 weeks postoperative. Kim and colleagues [31] permitted toe-touch weight-bearing with a crutch during the first three weeks and gradually increased to 50% of full weight until 6 weeks, and full weight-bearing without crutch was achieved at the end of the 6 weeks. In a recent review article by Young and colleagues [32], their senior author (Dr. Myers) proposed that the knee is braced and locked in 10 degrees of flexion and touch weight-bearing is allowed for the first two weeks. After the brace is removed, active ROM exercise is encouraged and weight-bearing increased by 25% of full weight per week to achieve full weight-bearing by the end of the 6 weeks. [32]

Considerations During Open Kinetic Chain (OKC) Exercise

The semimembranosus tendon is attached to medial meniscal posterior horn, and the medial meniscal posterior horn moves backward indirectly when the semimembranosus muscle is contracted (Fig. 2). Similarly, popliteus muscle contraction makes a backward movement of the lateral meniscus during early knee flexion with tibia internal rotation, because arcuate ligament connects the lateral meniscus and popliteus muscle securely and the lateral hamstring tendon attaches to the posterior horn of the lateral meniscus. [34] Moreover, the rollback of the meniscus is occurred with knee flexion, and load applied to the meniscal posterior horn with deep flexion is increased. Clinicians should consider this functional anatomy and biomechanics. The OKC exercise such as active hamstring curl exercise that involves flexion to beyond 90° under load is discouraged until 12 weeks postoperatively. [32]

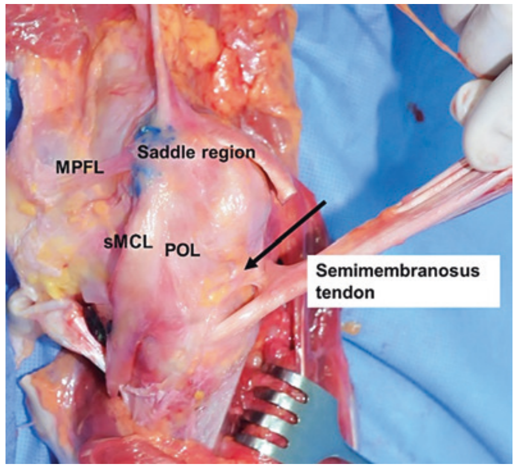

Fig. 2 See Chapter 2, Fig. 9. Semimembranosus has attachments (black arrow) to the medial meniscal posterior horn and posteromedial joint capsule, and they pull the meniscus during the knee flexion as progressive contracture of semimembranosus. MPFL: medial patellofemoral ligament; sMCL: superficial medial collateral ligament; POL: posterior oblique ligament. (Same as Chapter 2, Fig. 9)

Delayed Rehabilitation

Recently, our research on delayed rehabilitation after lateral MAT has been published. [35] We reported that delayed rehabilitation program showed less graft extrusion and joint space narrowing on weight-bearing x-ray, and reduced the progression of arthrosis on MRI compared

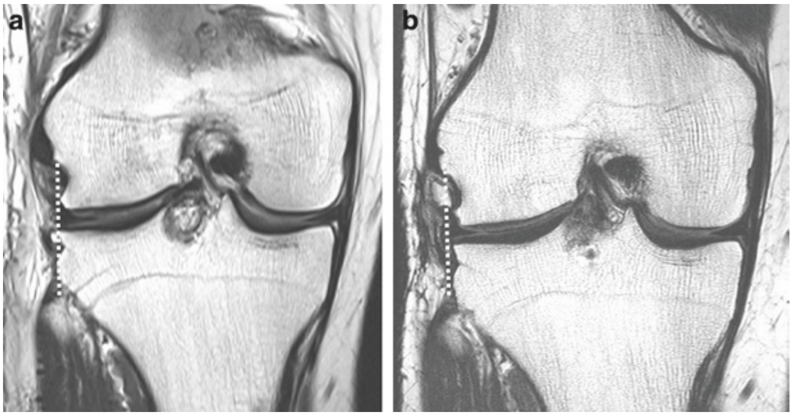

Fig. 3 **a** Presents an immediate postoperative coronal image of the right knee, and there is no graft extrusion. The coronal graft extrusion is not found at 26 months after lateral meniscal allograft transplantation (LMAT) and delayed rehabilitation program (Fig. 3b)

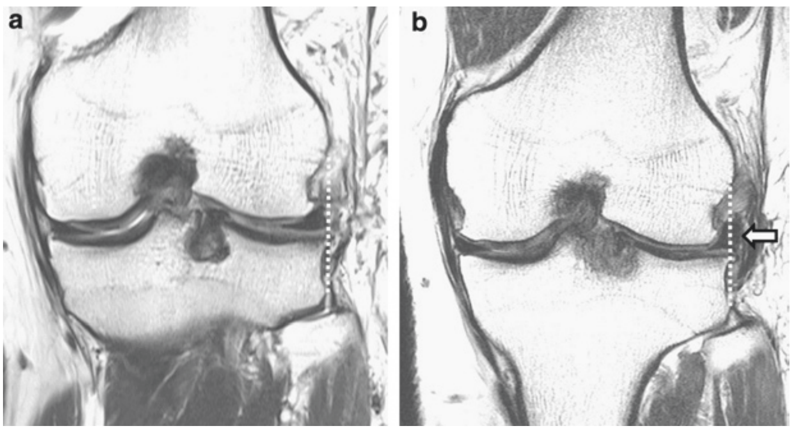

Fig. 4 **a** Shows an immediate postoperative coronal image of the left knee, and there is no graft extrusion. However, the graft extrusion (whited arrow) has been progressed in the patient who performed conventional at 24 months after LMAT and conventional rehabilitation protocol. (Fig. 4b)

with conventional rehabilitation protocol (Figs. 3, 4). [35]

The delayed rehabilitation aims to limit the initial ROM and minimize the load on the graft up to three months after MAT (Table 1). Lee and colleagues [36] showed that the mean amount of graft extrusion on serial MRIs was 2.87 mm, 2.95 mm, 3.03 mm, and 2.96 mm at 6 weeks, 3 months, 6 months, and 12 months after the MAT, respectively, without significance. In their study, 7 extruded cases (33.3%) at 6 weeks postoperatively remained extruded until the final follow-up at 12 months; however, the other 14 cases without graft extrusion at 6 weeks postoperatively did not show graft extrusion until 12 months postoperatively. [36] They concluded that a graft which extruded early remained extruded and did not progressively worsen, while a graft that did not extrude early was unlikely to extrude within the first year. Kim and colleagues [31] revealed that the graft extrusion and shrinkage did not progress between 3 months and 1 year period after MAT in both coronal and sagittal planes on serial MRIs. They reported that relative percentage of extrusion (RPE) in the coronal plane averaged 43.6% at postoperative 3 months, but there was no significant progression of graft extrusion at 12 months ($p = 0.728$). [31] Based on these results, we are focusing on minimizing graft extrusion within the initial three months.

Table 1 Comparison of conventional and delayed rehabilitations after meniscal allograft transplantation (MAT)

Rehabilitation type	Immobilization	Full range of motion	Brace	Weight-bearing	Isokinetic muscle exercise	Light running	Return to Sports
Conventional	for 1 week using long leg splint	at 6 weeks after MAT	Hinged brace for 7 weeks after splint off	Partial weight-bearing for 6 weeks	at 8 weeks after MAT	at 12 weeks after MAT	at 6 months after MAT
Delayed	for 3 weeks using long leg cast	at 12 weeks, 120 degrees in lateral MAT and full flexion in medial MAT	Medial or Lateral unloading brace for 9 weeks after cast off	Partial weight-bearing for 6 weeks	at 10 to 12 weeks after MAT	at 4 to 5 months after MAT	at 7 to 9 months after MAT

First Step (~3 Weeks)

The goal is to safely protect the fixation of the graft. The knee has been immobilized in full extension and slightly varus (in lateral MAT) or valgus (in medial MAT) with a long leg cast for 3 weeks (Fig. 5). We suggest that the three weeks of immobilization period can provide a positive effect on mechanical stabilization and biological healing of the graft protecting the healing process at the relatively weak menisco-capsular attachment. [37, 38]

Isometric quadriceps muscle strengthening and straight leg raising exercises are recommended immediately after surgery. Partial (Toe-touch) weight-bearing with a crutch is allowed during the first three weeks.

Second Step (4 ~ 6 Weeks)

The goal of this period is to prevent muscular atrophy and to improve neuromuscular control. Continuous passive ROM exercise is started at 4 weeks after cast off and the patients are aimed for a range 0 to 90 degrees in medial MAT, and 0 to 60 degrees in lateral MAT, respectively, by 6 weeks. We recommend that more restricted ROM exercise should be applied to the lateral MAT, because the lateral tibial condyle moves internally more than the medial side during knee flexion.

Patients should wear a medial or lateral unloading brace (DonJoy OA Adjuster; DJO Global) which reduces loading on the meniscal graft by 12 weeks after cast off. Weight-bearing is increased by 30% of body weight per week to achieve full weight-bearing by the end of the sixth postoperative week.

Initially, weight shifting exercise is performed in full extension for stimulation of proprioception. Patients can use the wobble board while sitting on a chair to gradually implement more active exercises that can stimulate proprioception without completely gaining weight on their knees.

Third Step (7 ~ 12 Weeks)

The goal of this step is to aim for normal walking, gaining of full range of motion, recovery of muscle strength, and proprioception. It is emphasized that the walking posture should be modified without the crutch to allow normal walking. The targeted ranges of motion by

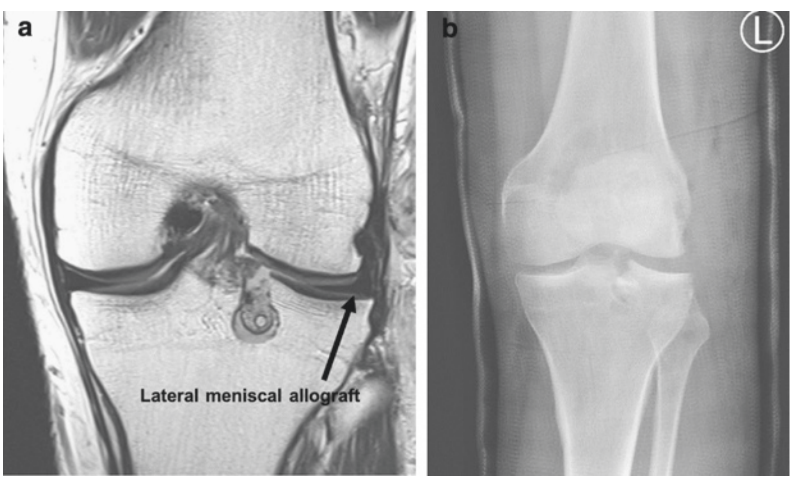

Fig. 5 **a** Immediate postoperative coronal magnetic resonance image of the left knee shows no extrusion of the graft. **b** The left knee is immobilized in full extension and slightly varus with a long leg cast after lateral meniscal allograft transplantation

12 weeks are 120 degrees and full flexion in lateral MAT and medial MAT, respectively.

At the beginning of the squat exercise, the squatting motion against the wall is limited to 45 degrees and is carefully performed to avoid hyperflexion. Hip exercises (abductor strengthening) using sandbags or tubing while standing are started. For muscle strengthening exercise, perform multi-directional squats, etc. by gradually increasing the difficulty level. Using a leg extension machine, the intensity is increased from isometric to isotonic exercises. The hamstring exercise begins with an active flexion with no resistance while standing or prostrate in this period. Active hamstring exercise should be restricted for 6 weeks after MAT based on anatomical mechanism. It is recommended that resistive hamstring exercise, which is heavily loaded on flexion movements, should be carried out after 12 weeks. When the muscle strength reaches a certain degree, the squats and balance walking exercise are conducted on unstable ground to improve the proprioception.

Fourth Step (13 Weeks~)

The goal of this step is to prepare return to sports activity with improvement of muscle strength and muscle endurance, and initiation of functional exercise. Functional training starts when the involved side reaches 70% or more of the uninvolved side by conducting isokinetic muscle strength tests, functional performance tests, etc. Light running and directional switching are allowed at 4 to 6 months and return to sports at 7 to 9 months according to the recovery of muscle strength and neuromuscular control, although strenuous contact sports are prohibited until 10 to 12 months.

Returning to Sports Activity

For the timing of return to sports (RTS) activities, 6 to 9 months after surgery seems appropriate based on the literature on the healing period of meniscus, but nothing has been established yet. In addition, recommendation regarding the intensity of RTS after MAT remains a point of contention. Some authors recommend lifetime avoidance of full sports activities; however, others allowed the patients to return to sports after as little as 3 months. [32]

Meniscal grafts are not fully restored to normal histology and function menisci and are more likely to induce degenerative changes and ruptures than normal tissues, hence, limiting strenuous sports activities is considered reasonable in the long-term plan. Patients should be informed about these limitations before MAT.

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Meniscal Allograft Transplantation: Surgical Technique

Michaela Kopka, Mark Heard and Alan Getgood

Abstract

This chapter will outline the surgical technique pearls and pitfalls of meniscus allograft transplantation. A thorough overview of our technique will be included, highlighting the key steps to perform a successful transplant. A planned order of surgical steps is also included when tackling multiple procedures with the goal of joint preservation.

Keywords

Meniscus allograft transplant · Surgical technique

Introduction

Meniscal allograft transplantation (MAT) has been utilized to treat the meniscus deficient knee for over three decades with multiple case series showing that it is an efficacious procedure. This chapter will focus on indications, patient evaluation, preoperative planning, surgical technique, and outcomes of lateral and medial MAT. As the lateral meniscus and tibiofemoral compartment are notably distinct from their medial counterparts, a thorough understanding of these disparities need to be fully understood and considered during surgical planning and execution to achieve a successful outcome.

M. Kopka · M. Heard
Banff Sport Medicine, Banff, AB T1L 1B3, Canada
e-mail: michaela.kopka@gmail.com

M. Heard
e-mail: sma.heard@gmail.com

M. Kopka · M. Heard
University of Calgary, Calgary, AB T2N 1N4, Canada

A. Getgood (✉)
The Fowler Kennedy Sport Medicine Clinic, University of Western Ontario, London, ON N6A 3K7, Canada
e-mail: alan.getgood@uwo.ca

Indications

The main indication for lateral and medial MAT is the same: functional meniscus deficiency resulting in unicompartmental pain and activity limitation in a young and compliant patient. Due to its unique anatomic and biomechanical features, the lateral meniscus is arguably more important than its medial counterpart in reducing the contact pressures across the tibiofemoral compartment and protecting the integrity of the articular cartilage. Its circular shape results in greater coverage of the articular surface area (80%) compared to the medial meniscus (60%), and thereby absorbs approximately 70% of force during loading [29, 31]. Biomechanical studies have shown that total lateral meniscectomy decreases joint contact area by 40–50% and consequently increases joint contact stresses up to

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200–300% [5, 11]. Successful lateral MAT can thus dramatically improve the longevity of the lateral tibiofemoral compartment.

Another important indication for MAT is as a concurrent procedure with revision ACL reconstruction when meniscus deficiency is deemed to be a contributing factor to instability [6, 18]. Musahl et al. [20] used a navigation system to measure anterior tibial translation in a cadaveric specimen undergoing the Lachman and Pivot Shift maneuvers. They showed that a complete medial meniscectomy resulted in significantly increased anterior tibial translation while resection of the lateral meniscus led to increased rotatory instability [20]. Therefore, a patient with significant anterior tibial translation and/or persistent rotatory instability and meniscus deficiency—in whom all confounding ligamentous deficiencies have been appropriately addressed—may benefit from MAT.

Recent advances in technology and surgical techniques have introduced a novel role for MAT, namely as an adjunct to articular cartilage restoration procedures [6]. The meniscus serves to decrease the contact stresses across the tibiofemoral compartment and is thus essential to protect a cartilage restoration procedure. Clinical studies reveal that cartilage surgery combined with MAT results in equivalent outcomes to MAT without a cartilage procedure [8, 28].

Not all patients with lateral meniscus deficiency are appropriate candidates for MAT. Relative contraindications described in the literature include.

- Uncorrected mal-alignment (valgus)
- Uncorrected ligamentous instability
- Osteoarthritis
- Inflammatory arthropathy
- Body mass index (BMI) greater than 35 kg/m^2
- Age over 55 years
- Involvement in high impact or high-level sporting activities
- Inability to comply with post-operative rehabilitation and activity restrictions
- Asymptomatic post-meniscectomized knee.

A recent systematic review showed that nearly half of all MATs are performed concomitant with either realignment osteotomy, anterior cruciate ligament reconstruction, or cartilage restoration procedure [27]. It is thus prudent to assess each patient independently and consider all contributing factors prior to proceeding with MAT surgery.

Patient Evaluation

As noted above, not all patients presenting with meniscus deficiency will be deemed appropriate candidates for MAT. A detailed patient evaluation is essential in order to identify those most suitable for reconstructive surgery. A key component of a thorough assessment includes a patient history aimed at delineating the nature and degree of symptoms. A pain history including the location, severity, exacerbating/alleviating factors, and associated symptoms should be obtained. The typical patient will complain of unicompartmental pain that is worse with impact activity and often accompanied by mild swelling. An account of all previous surgical procedures—including operative reports and arthroscopic images (if available)—should also be obtained. Any prior ligament and realignment procedures should be detailed. In addition, an understanding of the patient's activity level and post-operative expectations is critical to establishing their suitability for surgery. Activity modification can sometimes be enough to establish a quiet knee, and therefore avoid significant reconstructive surgery.

Physical examination should begin with an assessment of body habitus (i.e., body mass index, BMI), gait, and lower limb alignment. Notable varus and valgus deformities as well as the presence of a thrust should be identified. Inspection of the affected knee joint should focus on the presence of effusion, previous surgical scars, joint line tenderness, and range of motion. A comprehensive ligamentous exam is mandatory. Sagittal or coronal instability must be documented and taken into consideration when developing a surgical plan.

Standard anteroposterior (AP) and lateral weight-bearing radiographs are necessary. Tunnel (AP view in 45° of flexion) and axial views are helpful to better assess the degree of chondral wear in the tibiofemoral and patellofemoral compartments, respectively. Long leg hip-knee-ankle standing radiographs are useful to evaluate coronal alignment and measure mechanical axis deviation. Magnetic resonance imaging (MRI) is recommended as it can be helpful in identifying concomitant chondral pathology.

Preoperative Planning and Meniscal Sizing

Much of the preoperative planning will be completed by the patient evaluation detailed above. The history will dictate the need for surgical intervention, and the physical examination and imaging will determine if and what concurrent procedures are indicated. For example, in the setting of valgus malalignment, a lateral compartment unloading osteotomy will need to be performed either prior to or concomitant with MAT (Fig. 1). Similarly, treatment of any ligamentous insufficiency or focal chondral defects will need to be considered with an appropriate reconstructive procedure. The details of these procedures are beyond the scope of this chapter.

The next most important step in the preoperative planning process is the determination of appropriate meniscal allograft size. Correct sizing of meniscal allografts is necessary to optimize outcomes. Undersized grafts can increase contact stresses on the meniscal tissue, while oversized grafts can increase contact stresses on the articular surface. Dienst et al. [4] showed that meniscal grafts must be sized within 10% in order to recreate native joint contact parameters. A variety of sizing techniques have been described utilizing plain radiographs as well as computed tomography (CT) and MRI scans. The

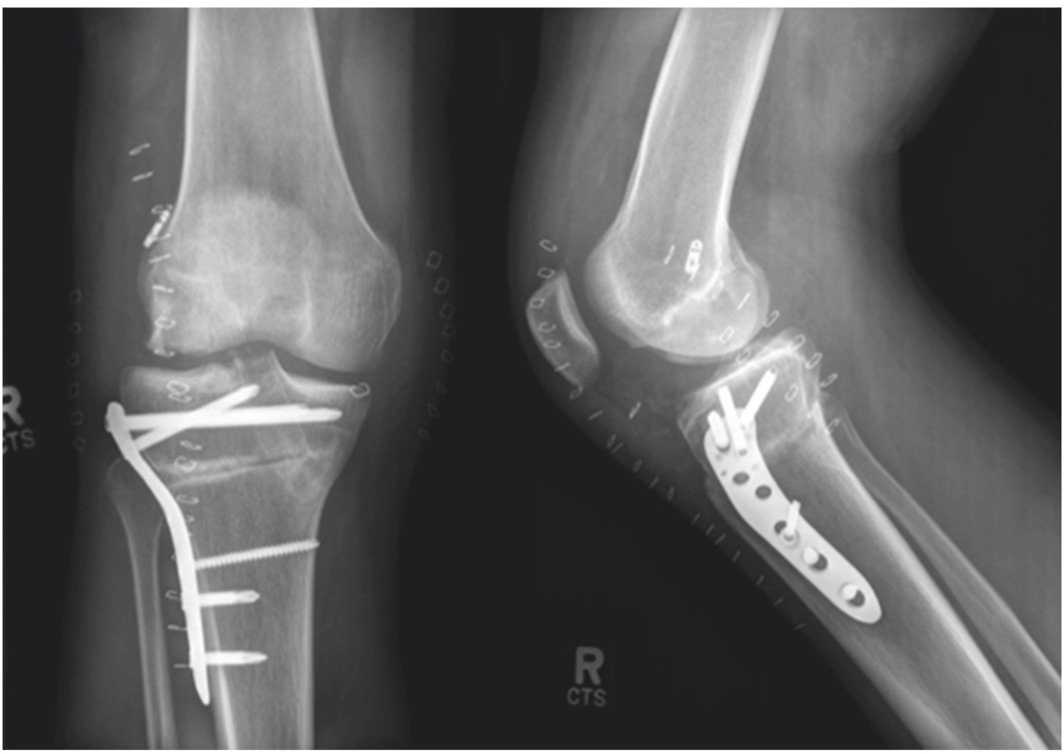

Fig. 1 Anteroposterior and lateral radiographs of a lateral MAT concomitant with lateral opening wedge high tibial osteotomy and osteochondral allograft transplantation to the lateral femoral condyle

most widespread method is likely described by Pollard et al. [24] in which meniscal width is measured on an AP X-ray from the tibial eminence to the periphery of the tibial plateau, and meniscal length is measured on a lateral X-ray from the anterior to the posterior margin of the tibial plateau. Magnification correction factors of 0.7 for lateral meniscus and 0.8 for medial meniscus, respectively, in order to generate a measurement within an error of 7.8% (Fig. 2). Although this technique is widely accepted, concerns have been raised regarding its reliability in sizing the lateral meniscus. Yoon et al. [36] measured the length of the lateral meniscus in cadaveric specimens and showed that Pollard's method yielded a measurement within 10% of actual meniscal size only 40% of the time. Consequently, he modified Pollard's technique and developed a best-fit equation which provided 92% accuracy in predicting correct meniscal size. This equation involves multiplying the length measured on standard lateral X-rays (as per Pollard's method) by 0.52 and adding 5.2 mm.

Although plain X-ray is certainly most cost-effective, CT and MRI can provide improved accuracy in allograft sizing as they account for meniscal shape in three dimensions (width, length, and height) [10, 19, 25]. Lastly, some authors argue that anthropometric factors including age, sex, and weight should be considered as these parameters have been shown to correlate with meniscal size [30].

Perhaps equally important to meniscal sizing is the process of allograft procurement. In general, meniscus tissue is harvested within 12–24 hours of the donor's death. Sterilization is necessary in order to decrease the risk of disease transmission. The most commonly used technique is that of fresh-frozen graft preparation and storage, in which the harvested meniscus is rapidly frozen to −80 °C. The advantages of this technique are that it allows storage of the graft for up to 5 years while maintaining its mechanical integrity [34]. An alternative is the use of fresh tissue. The meniscus can be stored fresh (in a 4 °C antibiotic solution containing the donor's serum) and transplanted within

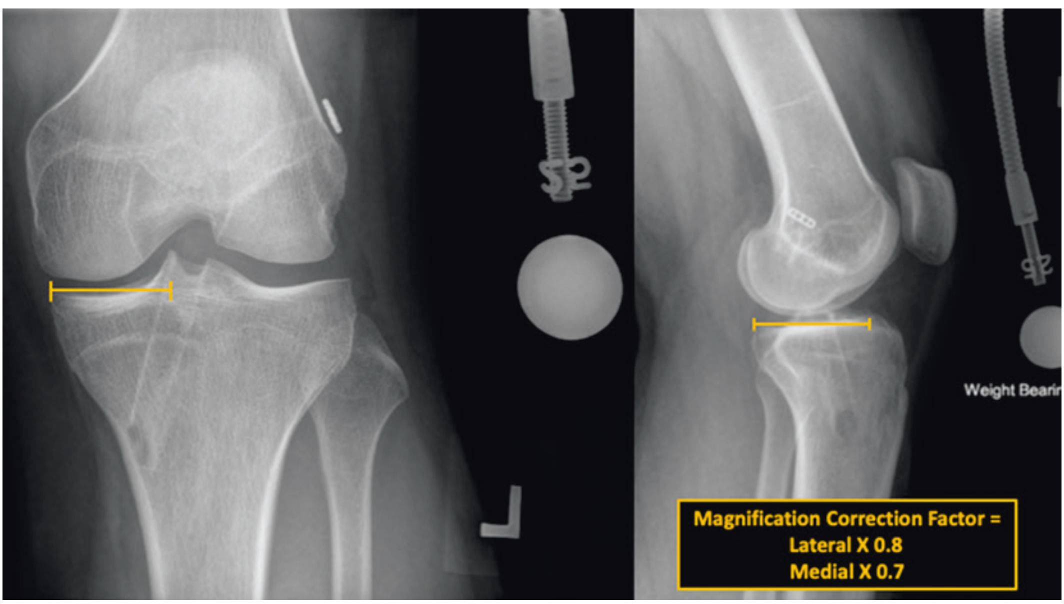

Fig. 2 The Pollard method for measuring meniscal size. Meniscal width is measured on an anteroposterior X-ray from the tibial eminence to the periphery of the tibial plateau, and meniscal length is measured on a lateral X-ray from the anterior to the posterior margin of the tibial plateau. Magnification correction factors of 0.7 for lateral meniscus and 0.8 for medial meniscus, respectively

10–14 days of harvest. Although this method has been shown to have the highest rates of cell viability, it carries the highest risk of disease transmission and can be both costly and logistically challenging [32, 34]. A 2015 survey of the International Meniscus Reconstruction Forum (IMReF) found that 68% of surgeons prefer to use fresh-frozen grafts while 14% use fresh grafts [6]. Other techniques that have fallen out of favor in recent years due to concerns of decreased cell viability and structural composition include cryopreservation and lyophilisation [34]. These also often involve gamma irradiation that has been shown to have negative effects on tissue structural integrity [34]. As such, the IMReF group recommends the use of fresh, non-irradiated meniscal allografts.

Surgical Technique

Surgical Team and Patient Positioning

As with any complex procedure, it is important to assemble an experienced team that can work cohesively together through the many surgical steps. An optimal team for efficient execution of a lateral MAT may include two orthopedic surgeons, a surgical assist (or third surgeon), a scrub nurse/technician, and a circulating nurse—all with comprehensive knowledge of the procedure. The lead surgeon is responsible for preparing the lateral compartment and creating the tibial trough. The second surgeon is dedicated to preparing the meniscal allograft and managing sutures during meniscus delivery and fixation. The surgical assist is utilized as necessary for graft preparation and delivery, suture management, and retraction during meniscal fixation. Given that MAT is not a routine procedure, this team approach allows for increased exposure and shared learning among multiple surgeons.

Appropriate patient positioning is essential for making a technically demanding procedure as easy as possible. The patient is positioned supine with a tourniquet applied about the thigh. The operative table should be flexed to 90 degrees at the level of the knees such that both legs hang freely. This allows for improved access posterolaterally while the operative limb is placed into a figure-four position. A 4–6 inch bump or bolster placed under the thigh further improves exposure and facilitates suture retrieval by increasing clearance from the operative table.

Medial MAT

The authors preferred method of medial MAT is the use of bone plugs in sockets. Soft tissue only techniques have been popularized particularly in Europe, the technique for which is essentially the same apart from the drilling of the socket and transplantation of the graft without the bone plug.

Graft Preparation

The meniscus allograft is thawed out in warm water. The graft is then trimmed of fatty tissue at the periphery. The coronary ligaments in the periphery of the meniscus may be left intact if a further anchor point is used to try and reduce the risk of post-operative extrusion.

For the posterior root attachment, an 8 mm coring reamer (Arthrex Inc. Naples, FL) is utilized to harvest the complete root attachment (Fig. 3). The length is cut to 8 mm so as to aid in the passage of the plug under the posterior cruciate ligament (PCL) to the posterior aspect of the medial compartment. Longer plugs can make this more challenging. Also, once posterior, longer plugs are more difficult to orient and insert into the posterior tunnel. The coring reamer system requires the passage of a collared pin, over which the coring saw is passed. On creation of the plug, a high strength #2 suture is passed through the plug, whip stitched into the tissue of the posterior root and then passed back through the plug.

The anterior root attachment site of the medial meniscus is highly variable (a small number of medial menisci only have soft tissue attachment). Only tissue with bony attachments will be supplied for transplantation. The anterior

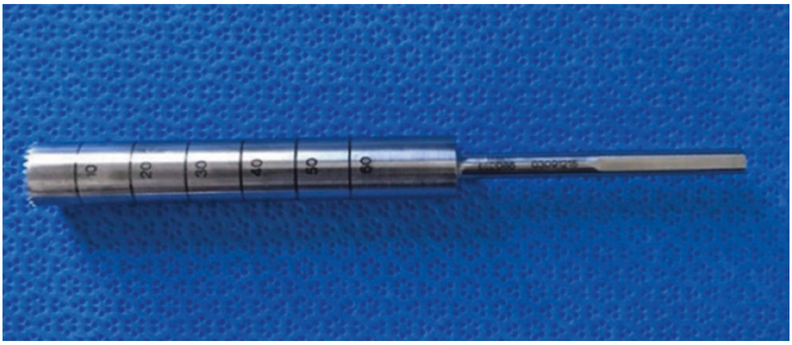

Fig. 3 Arthrex (Naples, FL, USA) coring reamer, used to prepare the bone dowel

root attachment may be either prepared as per the posterior bone plug in the socket or as a soft tissue attachment only. The former is prepared as per the posterior plug with the coring reamers. The soft tissue option is good if the allograft has a long soft tissue attachment. This can then be sharply dissected off the root attachment and whip stitched with a #2 high strength suture to be passed into a 4.5 mm bone tunnel. This technique is often preferable when performing concomitant ACL reconstruction.

Finally, to assist in the insertion of the graft, a traction suture is placed in the soft tissue portion of the meniscus transplant at the junction of the middle and posterior thirds. If the coronary ligaments are preserved, this suture can also be utilized as a further fixation point to reduce the risk of meniscal extrusion (Fig. 4).

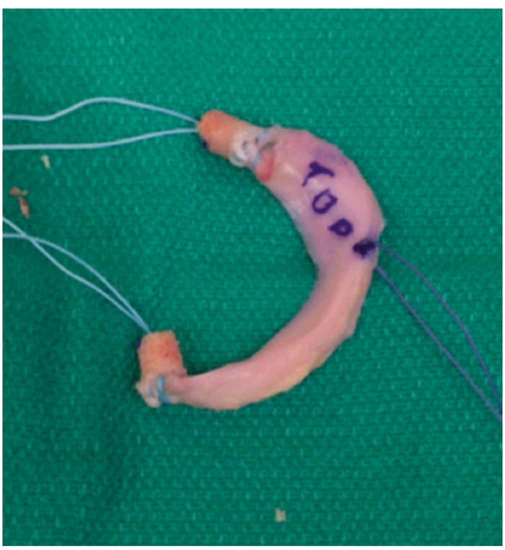

Fig. 4 Prepared medial meniscus allograft with high strength suture passed through bone plugs and traction suture applied to the junction of the posterior and middle third

The graft is then left on the back table until implantation, wrapped in a vancomycin soaked gauze (5 mg/ml) in an effort to reduce perioperative infection.

Arthroscopic Portals and Surgical Exposure

A high anterolateral and a large anteromedial portal are fashioned. The anteromedial portal should be placed adjacent to the patellar tendon and be large enough to place a little finger through to allow easy graft passage. This portal may also be utilized to gain access to the posterior root attachment with the aiming device. A small skin incision is made just above the level of the pes anserine tendons to drill the bone tunnels. At this stage, it is also helpful to make the approach to the posteromedial capsule to tie meniscal sutures. Doing this prior to arthroscopy will reduce the chance of fluid extravasation distorting tissue planes and make the surgical dissection easier. Following initial skin incision and blunt dissection through subcutaneous fat, the superficial fascia is incised followed by the leading border of the sartorial fascia. The pes anserine tendon group is retracted exposing the capsule and the medial head of the gastrocnemius tendon. The plane between the gastrocnemius and the capsule is developed and during repair, a retractor will be introduced to allow direct retrieval of sutures.

Meniscus Bed Preparation

This is similar for all techniques. In an effort to minimize "extrusion," a 2 mm remnant is maintained from anterior to posterior. This is typically in the "red zone" and is further stimulated for healing response using perimeniscal synovial abrasion and trephination (Fig. 5). The use of standard arthroscopic meniscal punches and right-angled punches are useful to aid in the successful resection throughout the tissue circumference.

In the tight medial compartment, a number of techniques can be used to aid visualization. Firstly, the medial collateral ligament (MCL) is pie crusted with an 18G needle. This is performed under direct visualization with the arthroscope, passing the needle multiple times over the meniscofemoral portion of the ligament, while simultaneously applying a mild valgus stress. The compartment should be seen to open gradually. To gain access to the posterior root attachment on the medial side, the knee can also be placed into varus. In the case of a wide medial plateau, the most medial aspect of the tibial plateau will act as a fulcrum and will allow the notch to open up. If it is still difficult to see the posterior horn attachment, the synovium under the posteromedial bundle of the PCL may be debrided with a shaver. Finally, if required, a thin posterior "mini" notchplasty is performed on the MFC and the medial tibial spine is partially removed with a burr.

The posterior and anterior root attachment sites are debrided most easily with a curved radiofrequency device so as to avoid soft tissue impingement during plug into socket insertion. The posterior insertion is placed just posterior to the tibial spine, while the anterior insertion is just anterior to the ACL footprint.

Socket Preparation

A meniscus posterior root-specific drill guide (Smith and Nephew Inc. Andover, MA) is placed through the anteromedial portal and positioned at the posterior root attachment site, adjacent to the PCL, inferior to the articular surface, and slightly anterior to the most posterior extent of the medial tibial plateau. A 2.7 mm guide pin is introduced over which a flip cutter cannula is placed, and inserted into the anteromedial tibial metaphyseal bone. The 2.7 mm pin is then removed and a 9 mm flip cutter inserted (Fig. 6). This is used as per the manufacturer's technique to produce a 10 mm deep socket. It is imperative

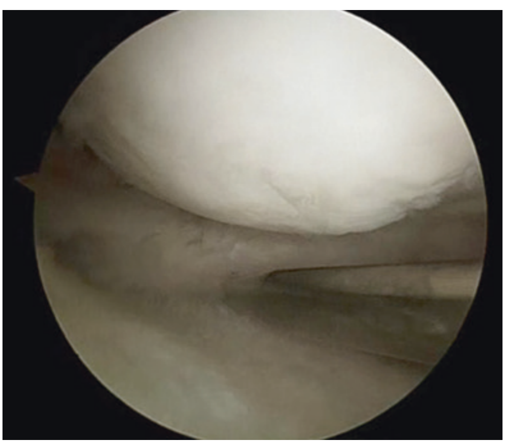

Fig. 5 Peri meniscal trephination with a microfracture awl to enhance inflammation and bleeding to improve the healing response

Fig. 6. 9 mm flip cutter in-situ, preparing 10 mm deep posterior root socket

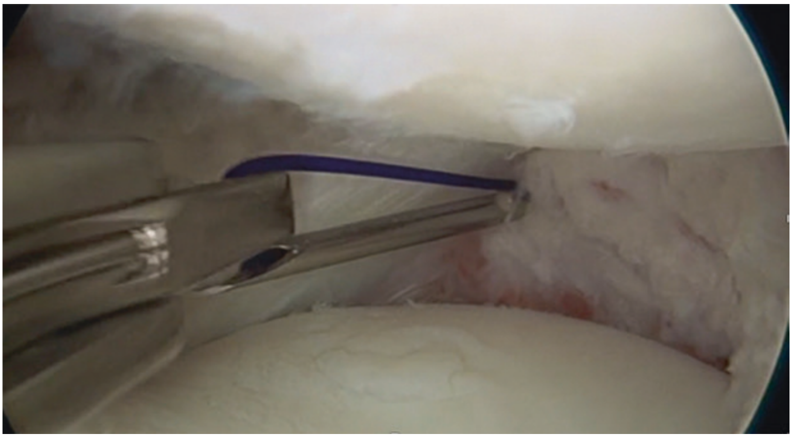

Fig. 7 PDS suture brought into the knee via an 18G needle (seen here during lateral MAT) to shuttle the middle traction suture, in order to aid in graft passage

to remove the soft tissue from the opening to avoid impingement during plug insertion. A passing suture is then placed through the cannula and retrieved through the anteromedial portal. Next, a loop of #0 PDS suture is brought into the knee from outside in at the junction of middle and posterior thirds of the meniscus. This is done utilizing an 18G needle and retrieved from the anteromedial portal (Fig. 7). Lastly, the anterior socket or tunnel is prepared. Following the insertion of the 2.7 mm guide pin, the same process can be followed for the creation of the socket using a flip cutter. Alternatively, a 4.5 mm drill can be drilled over the pin creating a small soft tissue bone tunnel that a long anterior root may be pulled down into. A passing suture is then again shuttled into the tunnel and brought out of the anteromedial portal.

Technical Pearl

To avoid tangling of sutures and a soft tissue bridge in the anteromedial portal, a suture manipulator (claw) is applied to the posterior root suture outside of the knee. The manipulator is then brought into the knee along this suture. Once inside the knee, the posterior suture is dropped and the middle suture grasped, following which the manipulator is brought out of the knee on the suture. On confirmation of no soft tissue bridge or entanglement, the manipulator is brought back into the knee on the middle suture, which is then dropped in the joint. The anterior suture can then be grasped, and the manipulator brought out of the knee again. This process may be repeated until there are no tangled sutures and the sutures are running freely in the portal. The use of a soft tissue cannula may also be used, but in the authors' experience this often takes up a lot of room and the graft is tricky to pass through it.

Graft Insertion

The graft is brought up to the knee and held medial of the knee in the orientation of insertion (Fig. 8). The posterior and middle sutures are shuttled into the knee first. The graft is then slowly introduced into the joint via the anteromedial portal with sequential traction on the two sutures. The arthroscope may be inserted into the anterolateral portal and a probe utilized to help push the bone plug under the PCL to the posteromedial compartment. The plug is then orientated in an appropriate position and the bone plug pulled into the socket (Fig. 9a, b). With the graft reduced in place, the anterior root is shuttled into the knee and the bone plug or

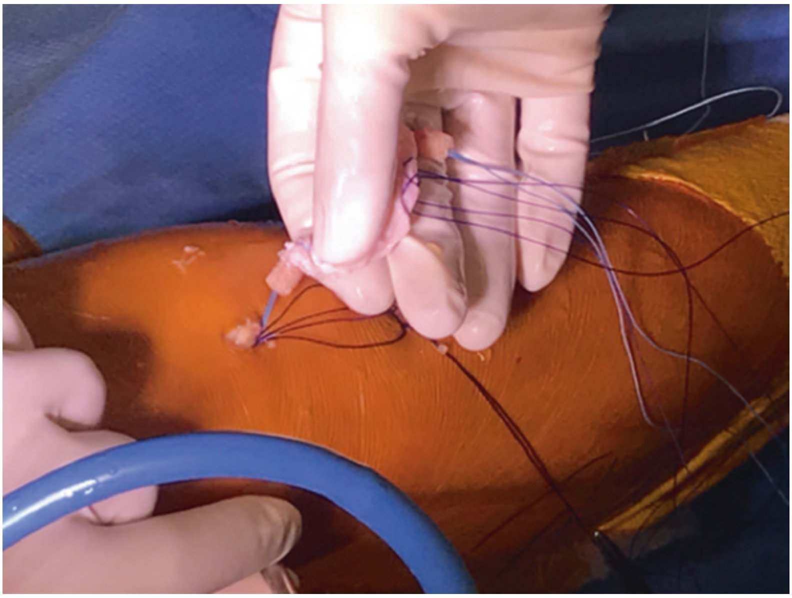

Fig. 8 Graft shuttled into the knee via the anteromedial portal

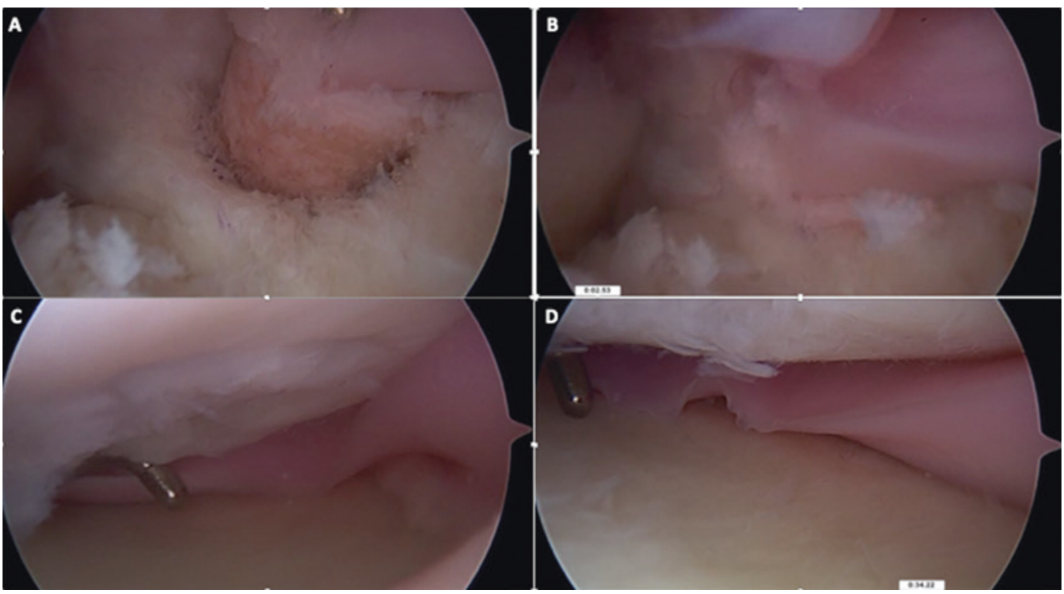

Fig. 9 **a**–**d** Posterior bone plug reduced into the posterior socket (**a** and **b**) with graft reduced back to periphery via the middle traction suture (**c** and **d**)

soft tissue insertion pulled into its socket or tunnel, respectively. If there is a size mismatch, it is imperative that the posterior insertion and body are anatomic. The anterior insertion can then be utilized to provide the appropriate tension/balance across the graft. The posterior root sutures are then tied over a cortical button, followed by the anterior sutures.

Graft Fixation

Our preference is to use an all-inside meniscus suture device on the posterior third and inside-out sutures for the middle and anterior thirds. The middle third is sutured first to avoid pushing the graft too posterior and unbalancing the construct. Zone-specific meniscal cannulae are used, placing #2–0 Fiberwire (Arthrex Inc. Naples, FL) on both the superior and inferior surfaces in a vertical mattress fashion. Two sutures are usually placed in the middle third initially followed by completion of the posterior third fixation. Two standard curve FastFix 360 (Smith and Nephew PLC., Andover, MA) suture devices are placed on the superior surface approximately 1.5 cm apart in a vertical mattress fashion. One further reverse curve device is then placed on the inferior surface, again in a vertical mattress fashion, between the two superior sutures. The remainder of the meniscus is sutured with inside-out sutures, retrieved from the medial incision and tied over the capsule. For every two sutures placed on the superior surface, one is placed on the inferior surface. An average of eight inside-out sutures and three suture devices are used per graft (Fig. 10).

Finally, if desired, the middle traction suture may be incorporated as a peripheral fixation suture using a bone anchor placed into the rim of the proximal tibia. On tying this we recommend visualizing the graft arthroscopically to ensure that the tensioning of this suture does not paradoxically cause extrusion of the graft, secondary to misplacement of suture or anchor.

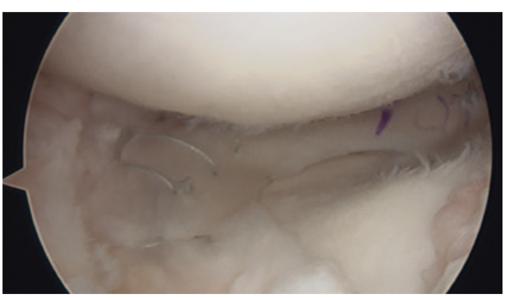

Fig. 10 Meniscus graft sutured in place utilizing a hybrid fixation technique; all inside sutures placed in the posterior third and inside-out sutures placed in middle and anterior thirds

Lateral MAT

Three basic techniques for root attachment in lateral MAT have been described: all soft tissue, bone plug, and the slotted trough technique. Although the use of bone plugs is preferable in the setting of medial MAT, the slotted trough technique has gained in popularity for lateral MAT [12, 22, 26, 38]. This is due to some key anatomic differences between the medial and lateral menisci. The close proximity of the anterior and posterior roots of the lateral meniscus (only 6–10 mm, according to anatomic studies) makes it amenable to the use of a single bone block [9]. Further, the trough for a lateral MAT is located more lateral in the notch and is thus less likely to interfere with the tibial tunnel in the setting of previous or concurrent ACL reconstruction [22, 26]. The slotted trough is the authors' preferred method for lateral MAT, and thus this section will focus specifically on describing the steps and pearls of this technique.

Graft Preparation

Prior to starting the procedure, the meniscal graft should be inspected to ensure appropriate tissue match and quality. First, confirm knee laterality (medial versus lateral) and the meniscal measurements. Next, inspect the graft for adequate bone stock (i.e., depth and height) at the tibial spine. Finally, ensure that the meniscal roots and peripheral tibial attachments have not been damaged during harvesting. Once the graft has been deemed suitable for transplantation, label the anterior and posterior horns with "A" and "P", respectively, and mark the "TOP" to ensure proper graft orientation during delivery.

Begin preparing the graft by releasing the meniscotibial attachments at the meniscal junction with a sharp blade. This should be done at the time of transplantation as the graft will shrink and distort if these attachments are

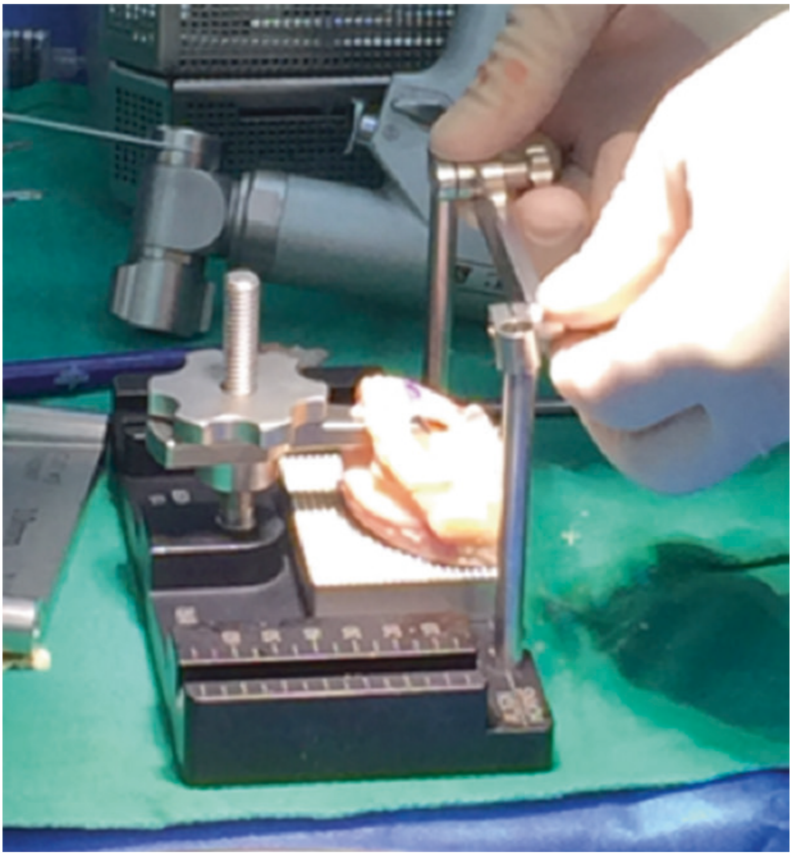

Fig. 11 The meniscal allograft is mounted into the jig and secured with a screw on the articular surface. The screw can loosen due to vibrations from the oscillating saw and must be frequently checked and re-tensioned during bone cutting

released during harvest. This step must be performed carefully to avoid accidentally releasing the meniscal roots. The roots of the lateral meniscus are significantly smaller than their medial counterparts. The posterior root measures only 28.5 mm^2 and is easily damaged by overzealous dissection [9]. The anterior root is typically longer and thinner and often quite intimate with the tibial insertion of the ACL.

The body of the meniscus must be completely released from the tibia so that it can be flipped into a vertical position prior to proceeding with the bone cuts. Performing accurate bone cuts is the most critical step of this technique. Although it is possible to free-hand, we prefer to use a specialized jig to assist with these cuts (Conmed, Utica, NY). The graft is mounted into the jig and secured with a screw (Fig. 11). Slotted guides are used to create two vertical cuts along the medial and lateral borders of the meniscal roots (Fig. 12). The distance between the cuts (and subsequent width of the bone block) should be 10 mm. It is worthwhile to note that the screw securing the graft can loosen due to vibrations from the oscillating saw and must be frequently tightened during cutting. Following the completion of the vertical cuts, a horizontal cut is made at a depth of 10 mm. A high strength #2 passing suture is then incorporated into the graft in a vertical mattress fashion at the junction of the anterior two-thirds and posterior one-third of the meniscus (i.e., the location of the popliteal hiatus).

Technical pearl: Referencing the horizontal cut off the tibial spine alone can lead to over-resection of bone if the spine is prominent. To

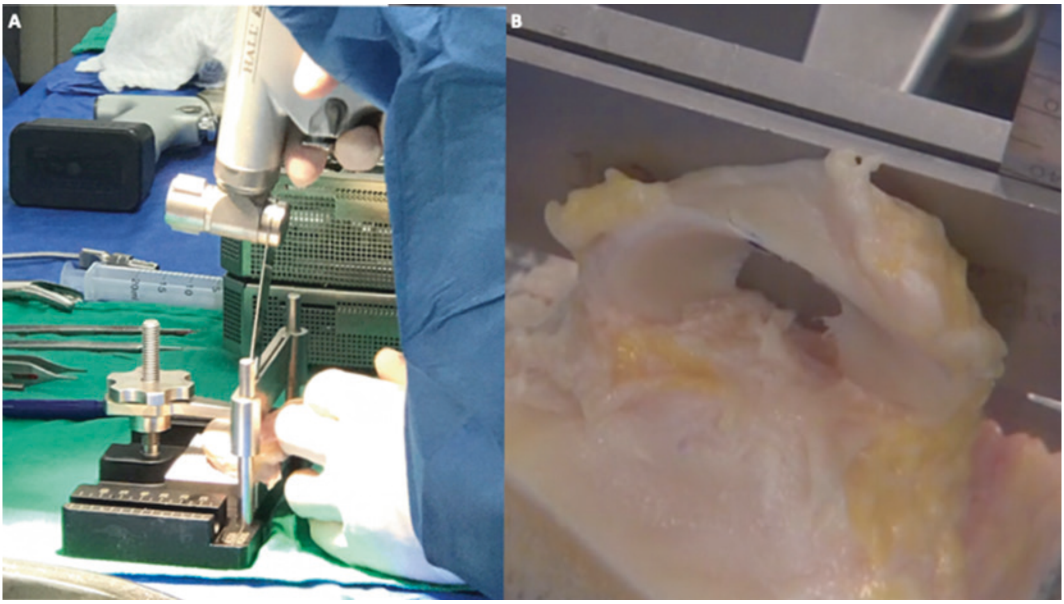

Fig. 12 Two vertical cuts are made along the medial and lateral aspect of the meniscal roots (**a**). The distance between these cuts is only 10 mm, and care must be taken not to damage the meniscal roots (**b**)

minimize this risk, measure and mark 10 mm of bone under each root prior to making the horizontal cut.

Arthroscopy and Meniscus Bed Preparation

Appropriate arthroscopic portal placement is important to facilitate the preparation of the meniscal bed as well as subsequent graft passage and fixation. The anterolateral portal should be made as proximal and anterior (i.e., close to the patellar tendon) as possible. This allows for optimal triangulation for debriding the anterior horn of the lateral meniscus and for creating a straight bone trough. A standard anteromedial portal is created to optimize suture passage during graft fixation.

A routine arthroscopy is performed and the condition of the articular surface in the lateral compartment is evaluated. It is critical to accurately grade the degree of chondral wear as this can be a deciding factor in whether or not to proceed with the lateral MAT. High-grade osteoarthritis (Outerbridge grade III/IV) has been shown to be associated with increased failure following MAT surgery [16, 23]. Once the decision to proceed has been made, the remnant lateral meniscal tissue is debrided back to a stable rim. Preserving a rim of the native meniscus is essential to mitigate the risk of graft extrusion (Fig. 13) [2, 33]. The remnant tissue is then stimulated with the use of a rasp or arthroscopic shaver. Take care not to damage the popliteus which can scar the capsule surrounding the hiatus in chronic cases. The most difficult area to prepare is the anterior horn which is intact in most cases. Viewing through the proximal anterolateral portal can provide improved perspective and visualization. A #15 blade or a 90-degree arthroscopic biter and shaver can also facilitate resection. A radiofrequency device can also be employed but should be used with caution near the articular surfaces.

Tibial Trough Preparation

This is the next most important step to ensure the appropriate fit and success of the MAT. The anterolateral portal is extended distally about 3–4 cm.

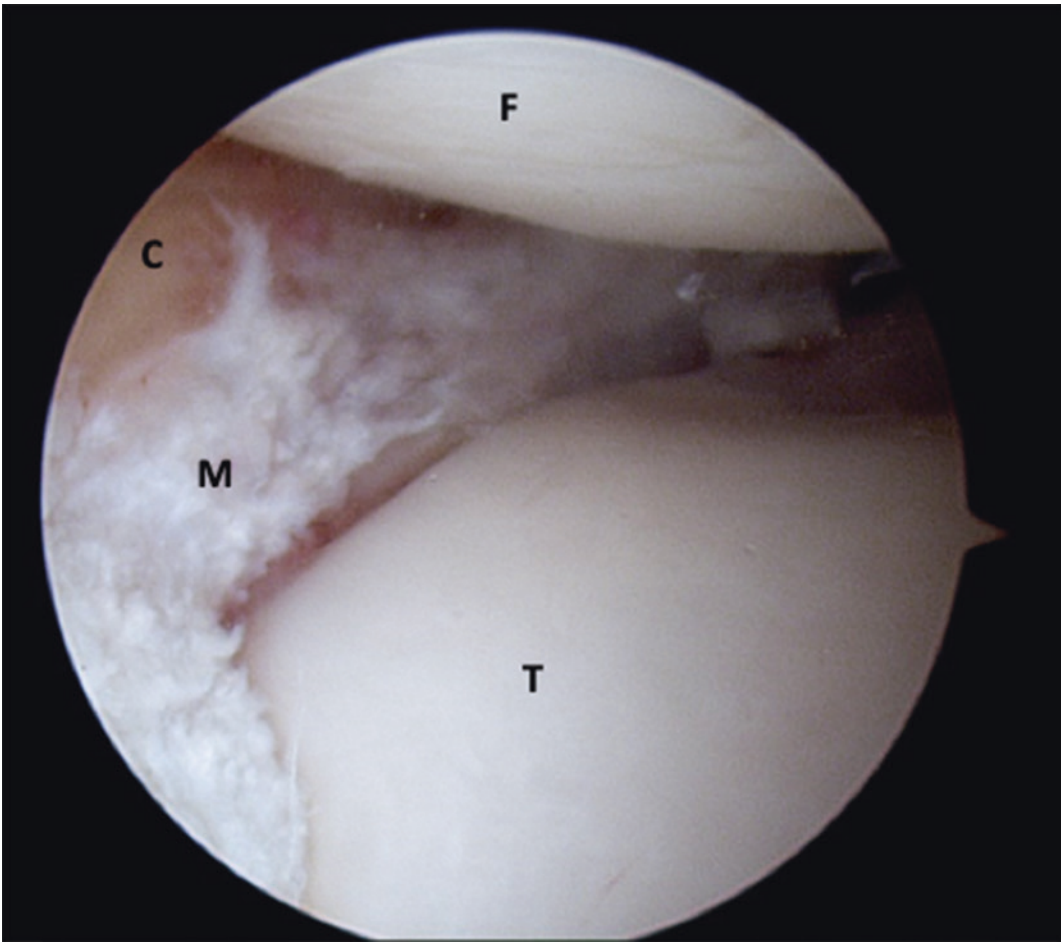

Fig. 13 Arthroscopic view of the lateral tibiofemoral compartment (F = femoral condyle, T = tibial plateau) with a remnant rim of the native meniscus (M = meniscal rim, C = capsule). The meniscal tissue is debrided to the "red zone" and a rim is preserved to minimize the risk of graft extrusion

A long 4/4.5 mm oval burr is used to create a groove along the lateral tibial spine (Fig. 14). This groove should be oriented parallel to the sagittal plane and care should be taken to avoid damaging the ACL. A guide is then used to drill an 8–10 mm socket under the groove (Fig. 15). A 3–5 mm rim of the posterior cortex is preserved in order to protect the neurovascular bundle and prevent posterior migration of the bone block. A rasp is used to create a dovetail-shaped groove that just breaches the articular surface in order to allow the meniscal roots to pass into the joint. A burr can be helpful to smooth the edges of the groove and ease graft passage (Fig. 16).

Technical pearl: It is better to err on the side of a deeper groove and a slightly recessed bone block as a proud graft can impinge on the lateral femoral condyle and damage the articular surface.

Graft Insertion

A self-retaining retractor is placed in the anterolateral arthrotomy and all soft tissues are cleared from the proximal tibia so that the trough is clearly visible. A 4–6 cm vertical incision is made posterior to the lateral collateral ligament

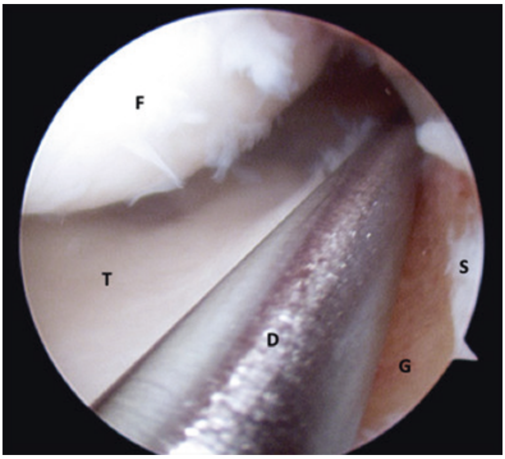

Fig. 14 A groove is created along the lateral border of the lateral tibial spine (S) with the use of an oval burr. The groove (G) should be oriented parallel to the sagittal plane. The drill guide (D) for the tibial trough is positioned in the groove

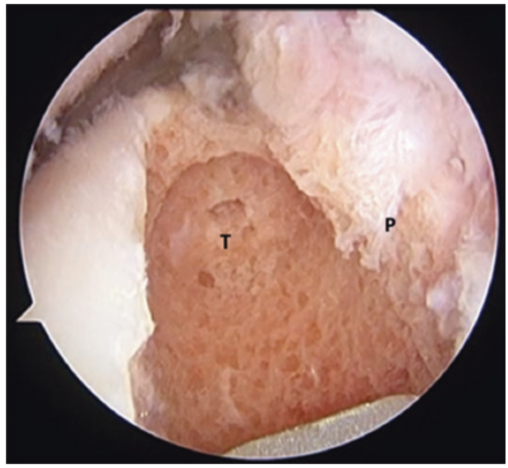

Fig. 16 The tibial trough with a rim of posterior cortex (P). Preservation of the posterior cortex prevents graft migration and protects the neurovascular bundle. (T = tibial plateau, S = tibial spine)

(LCL) and anterior to the biceps tendon. One-third of the incision is made proximal to the joint line and two-thirds are made below it. The plane between the lateral head of gastrocnemius and the posterior capsule is developed, and a blade retractor or spoon is inserted to protect the neurovascular bundle and ease suture retrieval. A zone-specific cannula is aimed just anterior to the popliteal hiatus and a shuttle suture is passed to exit through the posterolateral incision. This suture is used to pull the graft into the joint as the bone block is simultaneously inserted into the trough. A valgus force can help to increase the space in the lateral compartment and ease graft passage. The markings on the meniscus are used to ensure that the graft is correctly orientated as it is not uncommon for it to flip during delivery. It is also important to confirm the appropriate position of the meniscal roots in relation to the lateral femoral condyle and the ACL. If the meniscus is positioned too anterior, it may be necessary to resect more bone from the posterior cortex and re-deliver the graft.

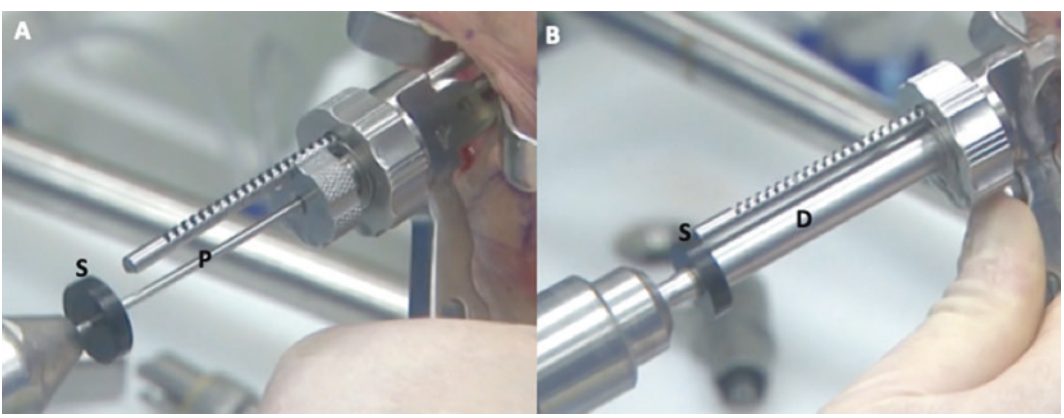

Fig. 15 The drill guide for creating the tibial trough includes a pin (P) and a cannulated 8–10 mm drill (D) with a depth stop

Graft Fixation

Various suture configurations have been described for securing the meniscal graft within the lateral compartment. Studies have shown that vertical mattress sutures provide the most stable repair and are thus considered the gold standard technique [2, 22, 26, 35]. Using zone-specific canulae, #2–0 Hi-Fi (Conmed, Utica, NY) sutures are placed in an alternating fashion on the superior and inferior surface of the meniscus. This step is likely the most technically demanding part of a meniscal transplant and it is essential to fully utilize the skills of your surgical team. Typically, the lead surgeon will maneuver the arthroscope and position the zone-specific guides. The second surgeon or scrub nurse will pass the needles, and the third surgeon will retrieve the sutures through the posterolateral incision and tie them over the capsule. Appropriate visualization is essential to avoid injury to the peroneal nerve. We recommend securing the posterior horn prior to the anterior horn to ensure the best possible fit of the graft. An all-inside meniscal suture device can be helpful for securing the most medial aspect of the posterior horn. Care must be taken when passing sutures in this location as the popliteal neurovascular bundle lies only 1.5–2.0 cm posterior to the posterior root of the lateral meniscus. The anterior horn is secured last via outside-in sutures through the anterolateral arthrotomy (Fig. 17).

Controversy exists in the literature with respect to the number of sutures required for a stable and successful lateral MAT. Unlike the medial meniscus, the lateral meniscus has minimal capsular attachments as it is not tethered along the popliteal hiatus or to the LCL. Consequently, it exhibits increased mobility and has been shown to translate up to 11.2 mm during knee range of motion [31]. This allows the lateral meniscus to maintain tibiofemoral congruency while protecting it from shear stress and subsequent injury. Accordingly, care must be taken not to over-constrain the meniscus as this will alter the native kinematics of the tibiofemoral compartment and increase the risk of graft failure. For this reason, we recommend using no more than a total of 5–10 sutures for securing the meniscal graft. Some authors have used as few as two stitches near the meniscal roots, but most studies advocate for a total of 6–10 sutures [2, 38]. Further research is needed to determine the exact number required to optimize outcomes.

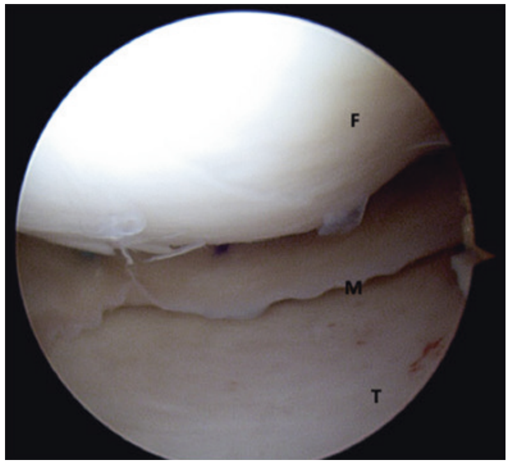

Fig. 17 Meniscal allograft (M) in place and secured with vertical mattress sutures. (F = femoral condyle, T = tibial plateau)

MAT and Concomitant Procedures

Nearly 50% of MATs are performed concomitant with other joint preserving procedures. In these circumstances, the sequence of surgical steps may need to be modified in order to avoid compromising the meniscal allograft. Table 1 describes the order of surgery when performing MAT with either ACL reconstruction, realignment osteotomy, or cartilage restoration procedure (Table 1).

Rehabilitation

The rehabilitation is the same for all graft types. Generally, the MAT will dictate weight-bearing and range of motion status if performed as a concomitant procedure. In the initial six weeks post-operative, a period of flat foot touch weight-bearing is paramount to avoid excessive

Table 1 Order of surgery for MAT and concomitant procedure

Concomitant procedure	Medial MAT	Lateral MAT
Anterior cruciate ligament (ACL) reconstruction	1. Meniscal bed preparation and socket/tunnel drilling 2. ACL tunnel drilling 3. Meniscus graft passage and fixation 4. ACL graft passage and fixation	1. ACL femoral tunnel drilling 2. Meniscal bed preparation and tibial trough drilling 3. Meniscus graft passage and fixation 4. ACL tibial tunnel drilling (through the meniscal bone block) 5. ACL graft passage and fixation
Osteotomy	1. Soft tissue approach for osteotomy (typically medial opening wedge high tibial osteotomy, thus medial approach and MCL release facilitates MAT) 2. Meniscal bed preparation 3. Osteotomy and plate application 4. Meniscal socket/tunnel drilling 5. Graft passage and fixation	1. Meniscal bed preparation and tibial trough drilling 2. Graft passage and fixation 3. Osteotomy and plate application (if performing a high tibial osteotomy, be sure to osteotomize well distal to the bone trough to avoid fracture propagation and destabilization of the MAT)
Arthroscopic cartilage restoration	1. Meniscal bed preparation and socket/tunnel drilling 2. Preparation of cartilage defect 3. Meniscus graft passage and fixation 4. Cartilage restoration procedure	1. Meniscal bed preparation and trough drilling 2. Preparation of cartilage defect 3. Meniscus graft passage and fixation 4. Cartilage restoration procedure
Open cartilage restoration	1. Meniscal bed preparation and socket/tunnel drilling 2. Meniscus graft passage and fixation 3. Open preparation of cartilage defect 4. Cartilage restoration procedure	1. Meniscal bed preparation and drilling 2. Meniscus graft passage and fixation 3. Open preparation of cartilage defect 4. Cartilage restoration procedure

strain on the root attachments. A hinged knee brace is used to limit the range of motion to 0–90 degrees of flexion to avoid excessive translation of the graft past 90 degrees. From six weeks, patients may weight bear as tolerated with the aid of an unloader brace. Full range of motion is encouraged; however, no loaded squats past 90 degrees are allowed until after three months. From three months onward, general neuromuscular re-training is progressed, with no ballistic impact activities allowed until after six months post-operative. While light jogging may then be re-introduced, contact pivoting sports are generally discouraged due to the risk of graft injury and failure.

Outcomes

A number of papers have been published outlining outcomes following MAT with follow-up out to 20+ years. Unfortunately, the majority are level III and IV studies with significant heterogeneity in graft procurement, surgical technique, concurrent procedures performed, and outcomes measured. There is even disparity in what constitutes failure, with the most common definition being the removal of the allograft or conversion to arthroplasty [21]. A 2019 systematic review by Novaretti et al. [21] assessed 658 patients (688 MATs) and found a mean survivorship of 73.5% at 10 years and 60.3% at 15 years. Additionally, two studies reported an overall survivorship of 50% and 15.1% at 19 and 24 years, respectively. De Bruycker et al. [3] performed a meta-analysis of 3157 MATs with a mean follow-up of 5.4 years and showed an overall survival of 80.9%. Increased age and BMI were found to be predictors of a poor outcome. Osteoarthritis has also been shown to correlate with worse patient-reported outcomes [16]. Parkinson et al. [23] performed a subgroup analysis of 125 MATs according to the presence of chondral wear. They showed that patients with no or partial chondral wear had an 85% lower risk of failure than those with full-thickness chondral loss on both femoral condyles. The presence of an isolated full-thickness chondral defect, however, does not negatively affect outcomes providing it is appropriately addressed at the time of surgery. Saltzman et al. [28] compared a matched cohort of patients undergoing MAT without a chondral defect and those who underwent a concurrent chondral restoration procedure (for a defect with a mean size of 4.4 cm^2) and showed no difference in outcomes between groups. In fact, concomitant procedures in general do not affect patient-reported outcomes following MAT. A systematic review showed no difference in outcomes in patients undergoing isolated MAT versus MAT combined with either osteotomy, ligament reconstruction, or cartilage procedure [14]. Lastly, lateral and medial MATs appear equivalent with respect to survivorship. Bin et al. [1] conducted a meta-analysis comparing outcomes of 287 medial and 407 lateral MATs at a minimum of 5-year follow-up. They showed no difference in overall survivorship; however, the lateral MAT group had significantly higher pain and Lysholm scores.

There is much debate in the literature with respect to the technique of meniscal root fixation that affords the best results. The most commonly employed techniques include suture-only, bone plugs, and bone trough/slot. A 2015 current practice survey of IMReF surgeons revealed that 74% prefer to use bone fixation (plugs for medial and trough/slot for lateral MAT) and 26% use a suture-only technique [6]. To date, the evidence has not been able to establish the superiority of one technique over another. In the meta-analysis by De Bruycker et al. [3], 54% of MATs were performed with suture-only fixation, 37% used a bone plug technique, and 9% did not report. The authors found no correlation between the surgical technique employed and overall survivorship or patient-reported outcomes. Another meta-analysis by Rosso et al. [27] of 1666 MATs also showed no difference in outcomes between suture-only and bone plug techniques. A matched cohort study by Koh et al. [13] compared patients undergoing lateral MAT with the keyhole bone plug technique to those undergoing arthroscopic suture-only fixation. They used post-operative MRI to assess the status of the graft, and excluded all patients with less than 2 years of follow-up as well as those undergoing any concomitant procedures. They were unable to show any difference in patient-reported outcomes, survivorship, or complications.

Although MAT is generally considered a salvage procedure and is not advocated in an active patient population, the young age and high activity level of eligible patients has prompted an investigation of return to sport outcomes. Zaffagnini et al. [37] reviewed 89 active patients who underwent MAT at a mean follow-up of 4.2 years and found that 74% were able to return to sport at a mean time of 8.6 months post-operative. Further, 49% were able to return to their pre-injury level of play. In a series of 12 professional soccer players undergoing MAT, 92% returned to soccer and 75% returned to play at a professional level. The mean time from surgery to the first competition was 10.5 months [17]. A systematic review of 9 studies that assessed return to sport as an outcome in active patients undergoing MAT showed an overall return to sport rate of 77%. Two-thirds were able to return to play at the same level [7]. Although these results are promising, return to high level—and particularly high impact—athletic endeavours remains a controversial issue and should be evaluated on a case-by-case basis.

Finally, MAT is a complex procedure that presents a number of potential complications. The most frequently reported complications include allograft tear (11.1%), arthrofibrosis (3.6%), and infection (2.0%) [21]. Graft extrusion is also a common concern with one study reporting some degree of extrusion on post-operative MRI in nearly all MATs at 10-year follow-up [33]. Despite its high prevalence, the clinical significance of graft extrusion remains to be fully elucidated. The current evidence does not reveal a correlation between graft extrusion and patient outcomes [15, 33]. A recent study by Lee et al. [15] stratified 45 MATs with a mean follow-up of 12.3 years into extrusion (>3 mm) and non-extrusion (<3 mm) groups. Primary outcomes included the Lysholm score, as well as the degree of joint space narrowing on weight-bearing radiographs. Although there was a significant increase in joint space narrowing in the graft extrusion group, there was no difference in the Lysholm score at final follow-up. Further research to better understand the impact of graft extrusion and how best to mitigate it is warranted.

Conflict of Interest

The authors declare no conflict of interest in relation to the content of this manuscript.

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Basic and Current Understanding of Articular Cartilage

Hyuk-Soo Han and Du Hyun Ro

Abstract

Articular cartilage has the unique structural and biomechanical properties to perform inherent functions including load-bearing, frictionless motion during several decades of life. It is composed of specialized cells, chondrocytes, and a largely abundant extracellular matrix which is regulated by various cytokines and growth factors. Articular cartilage shows a viscoelastic property to be able to respond differently to stress and loading. Articular cartilage injuries can be divided into three distinct types based on the depth of injury and each injury type has a different healing response and prognosis. However, intrinsic healing capacity is frequently insufficient for a full recovery. Differences in features between repair cartilage and native cartilage explain the deterioration of repair cartilage over time. Currently, regeneration of hyaline cartilage with biomechanical properties similar to native cartilage has been not achieved yet. Understanding the special architecture and biomechanics of articular cartilage will be the first step to fulfill these unmet needs.

Keywords

Articular cartilage · Chondrocyte · Collagen · Extracellular matrix · Proteoglycan · Cartilage injury · Cartilage repair

Introduction

Articular cartilage has the unique anatomical and biomechanical properties to perform inherent functions such as load-bearing, allowing joint motion, and withstanding many cycles of stress. It is composed of a small number of cells (chondrocytes) in lacunae embedded in an abundant extracellular matrix, consisting of collagen, proteoglycan, and water [1].

Although articular cartilage can endure a large range of loading conditions through life, cartilage injury may occur over aging as degenerative arthritis or by acute or chronic trauma during sports. Recently, traumatic cartilage injuries are becoming more frequent in young athletes [2]. In these young, active patients, arthroscopic surgeries including cartilage repair or regeneration may be necessary. Due to the limited healing capacity of articular cartilage in adults, cartilage lesions usually fail to heal spontaneously and may progress to degenerative arthritis. Under certain conditions or treatments,

H.-S. Han (✉) · D. H. Ro
Seoul National University Hospital, Seoul, Republic of Korea
e-mail: oshawks7@snu.ac.kr

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articular cartilage can be repaired. However, the repair tissue is commonly different from normal articular cartilage in the structure, mechanical properties, and durability.

This chapter discusses basic and current understanding of composition, structure, biomechanics, and injuries of articular cartilage to help clinical practice and scientific research about articular cartilage.

Composition

Articular cartilage functions to minimize friction in synovial joints and to absorb and spread mechanical loads to subchondral bone. For these functions, articular cartilage is composed of a water and a solid extracellular matrix [1, 3]. Also, articular cartilage has no vascular, lymphatic, or neural components, which minimize an inflammatory or immune response and self-healing capacity [1].

Articular cartilage is composed of specialized cells, chondrocytes, and a largely abundant extracellular matrix (ECM). ECM include 60–80% water, 10–20% collagen (mainly type II), 4–7% proteoglycans, and 1–5% other proteins [1, 3]. Chondrocytes are the only cell type present in the cartilage and play a role in synthesizing and maintaining the ECM.

Chondrocytes

The chondrocyte is the only cell type in articular cartilage and isolated in lacuna surrounded by ECM (Fig. 1). Chondrocytes are considered to be metabolically active, but low proliferative in physiologic conditions [3]. These cells can be differentiated from stem cells including several tissue-derived mesenchymal stem cells (MSCs) [1, 3]. Hydrostatic pressure by joint motion or mechanical loading makes synovial fluid flow through the matrix, which provides nutrients to chondrocytes. Also, mechanical stimuli induce mechanotransduction to chondrocytes. Therefore, unnecessary long-time immobilization or unloading of joints can cause degradation or thinning of articular cartilage [4–6].

Extracellular Matrix

A large hydrophilic mesh network with type II collagen and proteoglycan aggregate (10–20% of the total weight of articular cartilage) holds water (60–80% of the total volume of articular cartilage). Water is distributed in a gradient from surface (high) to deep (low) zone, which allows for deformation and load bearing in response to external forces, by shifting or in-out of water through the matrix [1, 3].

The major components of the ECM are type II collagen and proteoglycans. One of the specific features of hyaline cartilage is the

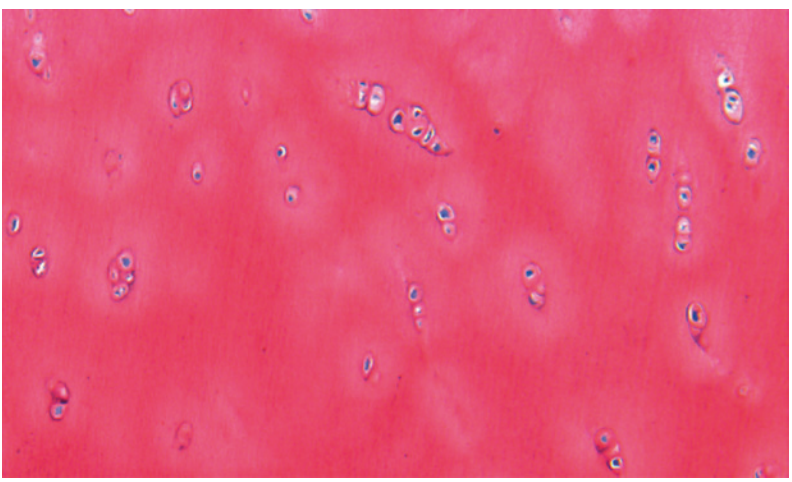

Fig. 1 Light microscopy of normal knee joint articular cartilage. Chondrocytes are found in the lacunae (100x, stained with Safranin-O)

predominance (90–95%) of type II collagen, which distinguishes it from repair fibrous cartilage that contain mostly type I collagen [7]. Collagen fibers act as a mesh to resist tensile force and fix the proteoglycan aggregates [7–10]. Type X collagen involves mineralization in the deep hypertrophic layer [7–10]. Proteoglycans are large ECM molecules composed of a protein core and bound hydrophilic glycosaminoglycan chains. Their primary function is the compressive strength of articular cartilage, by regulating the matrix hydration via high affinity for water. Multiple proteoglycans (aggrecan) are attached to a hyaluronic acid backbone, forming a proteoglycan aggregate. Major types of glycosaminoglycan are keratin sulfate, dermatan sulfate, and chondroitin 4- and 6-sulfate [7, 8, 10].

ECM synthesis is regulated by various cytokines and growth factors. Pro-inflammatory cytokines, particularly interleukin (IL)-1β and tumor necrosis factor (TNF)-α, contributed to the destruction of articular cartilage [7]. Transforming growth factor-β (TGF-β) can stimulate ECM synthesis and decrease the catabolic activity of IL-1β and the matrix metalloproteinases (MMPs) [7, 11]. However, TGF-β can inhibit type II collagen synthesis [12]. Fibroblast growth factor (FGF) can stimulate chondrocyte proliferation and stimulates ECM synthesis in injured joints [11]. Insulin-like growth factor-I (IGF-I) can stimulate DNA and ECM synthesis, decrease matrix catabolism except in aged and arthritic cartilage [11]. Because responses to growth factors are not fully understood, the clinical use of these potent biologic agents should be taken with great caution.

Structure

Articular cartilage in an adult is 2–5 mm in thickness and is organized into three zonal layers supported by a transitional calcified cartilage layer and subchondral bone (Fig. 2).

The superficial zone has a thin cover composed of collagen fibers which imparts the function sustaining against shear force (the lamina splandens) [8]. The chondrocytes in the superficial zone are flat-shaped and secret lubricin (also called superficial zone protein), a glycoprotein that functions as a critical boundary lubricant for articular cartilage and is normally isolated from synovial fluid. Collagen and water content is high, whereas the proteoglycan content is low compared with other layers [1, 3]. The middle (intermediate, transitional) zone consists of thicker and obliquely oriented collagen fibers and round-shaped chondrocytes. This layer has a transitional function resisting from shear to compressive forces. The deep zone has vertically oriented collagen fibers and columnar chondrocytes, the lowest water content, and the highest proteoglycan content [1, 3]. Primary function of this layer is to resist the compressive loads. The tide mark represents the upper border of mineralization in the calcified cartilage zone. This layer attaches and anchors the articular cartilage to the subchondral bone through interdigitating shape, type X collagen, and calcified ECM.

Biomechanics

Normal articular cartilage shows a viscoelastic property to be able to respond differently to stress and loading. On the slow rate of loading while walking, articular cartilage acts as a viscous material that allows absorbing the compressive force [13]. However, at the high rate of loading while running, articular cartilage responds like an elastic cushion [13]. This dynamic loading on articular cartilage influences chondrocyte metabolism and ECM synthesis or degradation through mechanoelectrical or mechanotransduction signals. It is not fully understood when articular cartilage is repaired or deteriorated after breakage of structural integrity.

Articular cartilage also has biphasic functions; the solid matrix that allows deformation resulting in increased contact areas and decreased contact stresses, and fluid lubrication by exudation and resorption that permits joint motion, while reducing friction and wear [8, 14]. Water content is up to 80% of articular cartilage

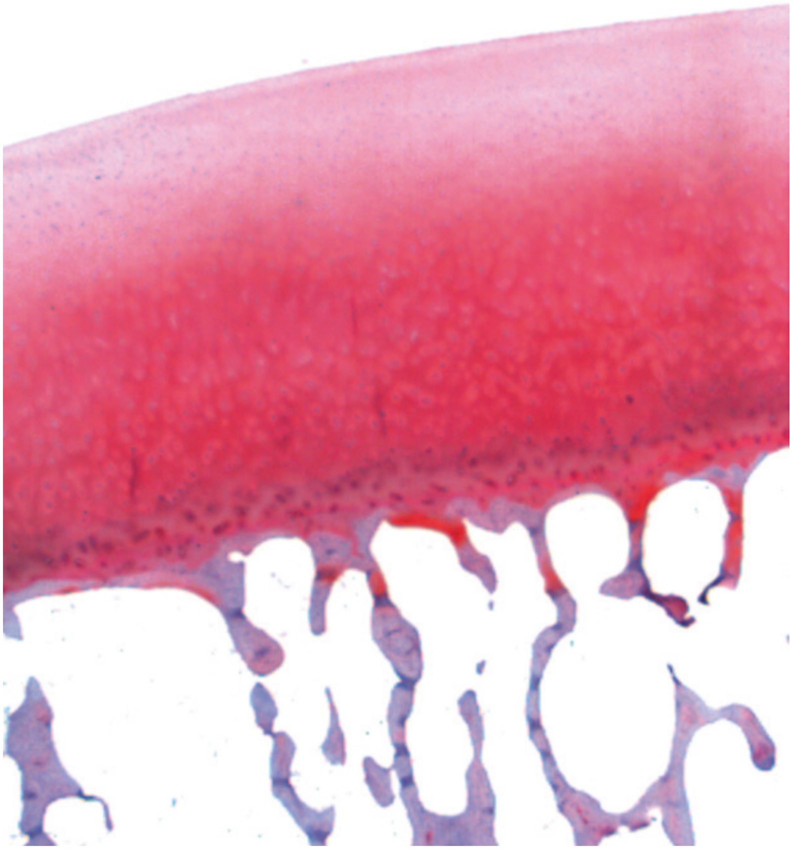

Fig. 2 Light microscopy of normal knee joint articular cartilage. Three zonal layers supported by a transitional calcified cartilage layer and subchondral bone are observed. (12.5x, stained with Safranin-O)

and it flows through the cartilage matrix by mechanical compression or pressure gradient [7, 8, 15]. The viscoelasticity of articular cartilage under compression is flow- and time-dependent [8, 14]. With a constant compressive force applied to cartilage, creep, and stress-relaxation is observed, which is based on hydrostatic pressure and water flow with the matrix [8]. Over time, water exits the matrix and the load applied is transferred to the proteoglycan–collagen matrix, causing matrix disruption. During cyclic loading in physiologic conditions, complete support by the solid matrix does not occur [8, 14].

The viscoelasticity of articular cartilage under pure shear force is flow-independent [8]. The tissue resistance against shear force comes from the collagen matrix in the middle zone. In degenerated cartilage, collagen matrix can be broken with significant shear force, causing partial-thickness cartilage defect. Also, excessive compressive load in trauma induces a shear force at cartilage–subchondral bone interface, causing full-thickness cartilage defect [7, 8].

In animal models, regular running exercise can increase proteoglycan in the matrix and overall cartilage thickness [16]. Evidence from in vitro studies demonstrate that mechanical signals within a physiological range of intensity, duration, and frequency have potent anti-inflammatory effects which counteract the catabolic signals induced by IL1β or TNFα [16]. Also, after cartilage injury, continuous passive motion helps cartilage repair. However, the amount of exercise which helps maintaining cartilage homeostasis is various according to each individual and cartilage status. Further research is required to examine and determine the effects of exercise.

Articular Cartilage Injury

Although articular cartilage lesions are highly prevalent (~60% of arthroscopies), the progression of lesions is rarely reported [17, 18]. Most studies documented radiological progression included osteoarthritis patients, not subjects with pure cartilage defects [18].

Articular cartilage injuries can be divided into three distinct types based on the depth of injury (1) pure cartilage lesions with variable depth down to the calcified tidemark and (2) cartilage lesions involving subchondral bone, (3) microdamage from impact. Each injury type has a different healing response and prognosis. The size and depth of lesion are important factors and it is also influenced by age, obesity, ligamentous or meniscal injury, and alignment [19–21].

It has been reported that chondrocyte replication occurs in the superficial zone and a deeper zone of the immature individual. However, after the development of the tidemark at maturity, the mitotic activity of chondrocyte is rarely observed.

In animal models, the chondrocytes adjacent to the injury demonstrates increased mitotic activity and proteoglycan synthesis for 1–2 weeks [22].

This intrinsic healing capacity is frequently insufficient for full recovery.

Although cartilage is avascular and has a limited reparative response, subchondral bone underneath the cartilage has an abundant blood supply and extrinsic cell sources. Therefore, the response of cartilage injury involving the subchondral bone differs from that of pure cartilage injury.

Pure Cartilage Lesions

Because there is no additional cell source, cartilage lesions confined within the matrix in mature individuals show little spontaneous healing [23, 24]. The repair of this superficial partial-thickness cartilage lesion depends on the chondrocytes adjacent to the injury site. Interestingly, many of the surviving cells in the region of the injury subsequently undergo a proliferative response in an attempt to repair the tissue. Although type II collagen and matrix macromolecule synthesis is increased in the surviving chondrocytes (which proliferate and form clusters in the periphery of the injured zone), the increased metabolic and mitotic activity is brief, after which the synthesis rates fall back to normal [3, 25].

Even though some MSCs in the synovial fluid were identified, it is difficult to expect a large role due to the characteristic of cartilage which prevents cell attachment.

Cartilage Lesions Involving Subchondral Bone

Articular cartilage lesions that involve the underlying subchondral bone show different responses. MSCs from bone marrow and peripheral blood can access the lesions and form a super-clot to be fibrocartilage in later [26]. The subsequent release of cytokines and growth factors promotes additional cell migration, proliferation, differentiation to chondrocyte-like cells, and matrix formation. By 6–8 weeks, the repair tissue contains a high proportion of chondrocyte-like cells, which synthesize a matrix containing types I, II collagen and aggregating proteoglycans [3]. However, this intrinsic repair forms fibrous cartilage containing a significant proportion of type I collagen, not hyaline cartilage [27, 28].

Concurrently, immature bone within the bony defect appears and is getting mature by endochondral ossification to resemble primary bone. However, the composition of the cartilage is different from normal cartilage. Subsequently, degeneration of matrix occurs from surface fibrillation, followed by loss of matrix. By 12 months, the remaining cells typically assume the appearance of fibroblasts, with the surrounding matrix composed primarily of densely packed type I collagen fibrils [3].

Recovery from Impact

The response of articular cartilage after a single high impact differs from that of repetitive moderate impacts. Chondrocyte apoptosis, matrix degradation, surface fibrillation, and subchondral bone edema have been observed [29]. In a rabbit model of chondral injury, up to 34% of chondrocytes in the area undergo apoptosis, in contrast to a 1% basal rate of apoptosis [30]. Over a certain threshold level of impact load, the cartilage may be sheared off in part or full thickness from subchondral bone. Repetitive injuries induce thickening of tidemark and calcified cartilage, which results in an increase in stiffness and arthritic changes [29]. However, the point at which repetitive injury becomes irreversible is unknown.

Repair Cartilage

For isolated articular cartilage injuries, regeneration with hyaline cartilage that has the biomechanical properties of native cartilage is one of the great challenges in orthopedics. Several surgical treatments have been used including arthroscopic debridement, abrasion arthroplasty, multiple drilling or microfracture of subchondral bone, autologous osteochondral graft transfer, osteochondral allografts transplantation, and autologous chondrocyte implantation [31, 32]. Among them, regenerative procedures demonstrated incomplete healing of cartilage lesions to fibrous cartilage [31, 32]. Studies showed that the repair process starts with blood clot formation. Then, mesenchymal cells begin to penetrate the fibrin matrix, and within a matter of weeks, this is completely replaced by a vascularized, scar-like tissue [26]. However, cells in repair cartilage usually have a fibroblast-like shape and ECM consists of dense unorganized collagen fibers [31, 32]. This repair tissue manifests neither an arcade-like organization of its fibers nor a well-defined zonal stratification of its chondrocytes. Its biochemical composition is indeed more akin to fibrous than to hyaline cartilage [33], and its mechanical competence is significantly inferior to that of the latter [34].

Fibrous repair cartilage shows loss of the proteoglycan content and surface fibrillation over time. The main collagen in the repair tissue was type I. Type II become predominant and continued to be enriched up to one year, but type I still persisted as a significant constituent of the repair tissue. Repair cartilage never fully resembled normal cartilage [33]. In addition, the collagenous fibrillar network of repair cartilage has been found neither to project into native tissue nor to intermingle with its fibrils [35]. Changes in cartilage as well as subchondral bone pathology, especially bone cyst formation have been also noted [36]. These difference in features between repair cartilage and native cartilage explains the deterioration of repair cartilage over time [37].

Mechanical Effect on Cartilage Repair

The joint motion has been known to have a role not only in the formation and development of articular cartilage but also in cartilage repair [4, 38]. A certain amount of weight-bearing and motion may improve the cartilage healing [38]. In numerous animal models, a continuous passive motion was found to enhance cartilage repair compared to immobilization [4–6]. However, the mechanism of enhancement was not fully understood and clinical benefit was not definitely proved.

Several studies reported the effects of joint distraction while allowing joint motion on arthritis [39, 40]. They demonstrated the increase of joint space and clinical outcome improvement. Cartilage regeneration after high tibial osteotomy has been reported [41–43]. The unloading of the medial joint through high tibial osteotomy is thought to improve clinical symptoms and to slow or restore joint cartilage damage [41–45]. However, the major factors that influence the regeneration of cartilage defect remain to be determined.

Conclusion or Summary

Articular cartilage has unique structural and biomechanical properties allowing frictionless motion and sustaining mechanical loading throughout several decades of life. However, a limited healing capacity of articular cartilage leads to incomplete healing or progressive deterioration after cartilage injuries. Currently, regeneration of hyaline cartilage with biomechanical properties similar to native cartilage has been not achieved yet. Understanding the special architecture and biomechanics of articular cartilage will be the first step to fulfill these unmet needs.

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Cartilage Repair with Autogenous Cells

Ho Jong Ra

Abstract

- Full-thickness osteochondral lesions of the knee are common.
- The management of chondral defects is challenging; microfracture, autologous chondrocyte implantation, osteochondral autograft transfer/osteochondral allograft transplantation.
- ACI (autologous chondrocyte implantation), a cell-based therapy, was introduced in 1987 and the first clinical report was published in 1994 by Brittberg et al.
- Third-generation ACI, MACI (matrix-assisted autologous chondrocyte implantation): matrix is seeded with cells and implanted in the cartilage lesion.
- Cell-based methods, especially ACI and MACI, have resulted in impressive functional, histological, and radiographic outcomes for periods of up to 20 years in several large studies resulting in hyaline-like cartilage formation in larger lesions.
- Despite progress using cell-based therapies, there are still several limitations. So future therapies need to overcome the disadvantages associated with ACI.

Keywords
Articular cartilage injury · Osteochondral lesion · Cell-based therapy · ACI · MACI

Introduction

Full-thickness articular cartilage injuries and osteochondral lesions of the knee are common and may lead to significant pain and morbidity. Previous reviews demonstrated articular cartilage lesions in approximately 60% of patients undergoing knee arthroscopy [1, 2]. Partial-thickness articular cartilage defects are marked by the loss of proteoglycans, disruption of the collagenous network, and thus cell death [3, 4]. Small lesions gradually deepen, leading to full-thickness defects [5, 6]. Chondral defects are associated with higher contact stresses in the adjacent intact cartilage [7–9]. If left untreated, full-thickness chondral defects can lead to progressive cartilage degeneration with symptoms such as pain, swelling, and joint dysfunction, and ultimately, 'early-onset' osteoarthritis may occur [10]. And thus often require surgical intervention.

H. J. Ra (✉)
Department of Orthopaedic Surgery, College of Medicine, Gangneung Asan Hospital, Ulsan University, Gangneung, Republic of Korea
e-mail: os_rahj@naver.com; osrahj@gmail.com

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The management of chondral defects is challenging. Focal lesions in knee articular cartilage can be addressed by a myriad of techniques. Lesion size, characteristics, patient age, and surgeon experience often guide treatment decisions for these defects. Surgeons commonly use marrow stimulation procedures such as microfracture/drilling or chondroplasty for smaller lesions. Grafting procedures are usually reserved for larger defects. Examples of grafting procedures include osteochondral autograft or allograft transplantation, autologous chondrocyte implantation (ACI), and minced allograft procedures. Overall, knee alignment is often assessed, and surgeons may choose to supplement cartilage surgery with osteotomies (distal femoral [11], proximal tibial [12, 13], and tibial tubercle [14]) to address pathologic malalignment. Concurrent corrections in tibiofemoral or patellofemoral alignment have been associated with improved outcomes following articular cartilage surgery [14–18].

Over the past decade, the majority of cartilage defects have been managed with simple debridement (chondroplasty) or marrow stimulation procedures (abrasion or microfracture). Reviews [19–21] indicate current repair techniques such as abrasion arthroplasty and microfracture do not fully restore tissue [22, 23], and resulting fibrocartilage lack the mechanical properties of hyaline cartilage [24]. Clinical outcomes depend on patient age and activity [25]. Researchers have considered tissue engineering approaches such as ACI to manage articular cartilage defects.

Autologous Chondrocyte Implantation and Matrix-Assisted Autologous Chondrocyte Implantation

New, ambitious regenerative procedures are emerging as potential therapeutic options for the treatment of chondral lesions, aiming to re-create a hyaline-like tissue, thus restoring a biologically and biomechanically valid articular surface with durable clinical results. ACI, a cell-based therapy, was introduced in 1987 in Sweden, and the first clinical report showing satisfactory results for isolated femoral condyle lesions was published in 1994 by Brittberg et al. [26] based on the original animal studies of Bentley and Greer in the 1970s [27] with the aim of achieving normal hyaline cartilage repair of osteochondral defects [28]. Since then, several studies have followed, ACI has been available for several decades and, over time, has gone through several derivations. ACI has two main steps, the first-stage procedure requiring an initial arthroscopic biopsy to harvest chondrocytes for isolation and expansion by proprietary means, and followed by implantation of the cells during a second-stage procedure [26]. Containing expanded cells was initially a challenge, the cartilage defect coverage in first-generation ACI is made with a periosteal patch. Second-generation ACI technique has since been introduced, in which the previously used periosteal patch has been replaced with a membrane made often of collagen type I/III. This modification has been driven by an effort to reduce operating time and minimize the complications related to the periosteal use (periosteal hypertrophy and overgrowth), procedural invasiveness, and technical demands associated with the harvest and use of a periosteal flap cover [29, 30]. In third-generation ACI, a matrix is seeded with cells and implanted in the cartilage lesion, is so-called MACI (matrix-assisted autologous chondrocyte implantation). These treatments use a chondroinductuive or chondroconductive matrix usually seeded with autologous cells in controlled conditions to improve mechanical properties before the surgery. It is believed that third-generation ACI has an even chondrocyte distribution and there is no need for sutures or a coverage which reduces the time of the surgery and the surgical exposure [29].

The indications for an ACI treatment in a knee cartilage lesion are well-motivated patients under 55 years old, with pain, swelling, locking, or catching with a grade II or IV cartilage lesion. ACI has been used to restore focal defects between 2 and 12 cm^2. However, it has been used in lesions up to 26.6 cm^2. In defects under 2 cm^2, ACI is indicated as a salvage procedure with poorly reported outcomes. The best location is the femoral or patellar articular surface without a kissing lesion in the opposite articular surface. ACI is contraindicated in patients with inflammatory arthritis or with an articular infection associated lesions described above must be considered and included in the treatment plan [29, 31–33].

Surgical Technique

The surgical technique of both ACI and MACI involves a two-stage approach. The first stage consists of the assessment of the joint and biopsy of healthy cartilage. At the time of arthroscopic assessment of the joint, either as an evaluation of the degree of suspected articular damage or when an articular defect is found in conjunction with some other intra-articular pathology such as an anterior cruciate ligament or meniscal tear, chondral biopsy samples are taken for autologous chondrocyte tissue culture. The cartilage biopsy samples are harvested from the non-weight-bearing areas such as the outer edge of the superior medial or lateral femoral condyle or the inner edge of the lateral femoral condyle at the inter-condylar notch. Approximately weighing 200–300 mg of healthy articular cartilage are necessary for culture. The biopsy specimen is then placed in the biopsy vial and sent to a commercial facility, where the culture process occurs. The harvested cartilage fragment is processed to achieve chondrocyte isolation and expansion to a high chondrocyte density in vitro, usually between 5 and 10 million cells over a period of 4–6 weeks [32]. In the second stage, the chondrocytes are implanted into the defects. For the implantation procedure, an arthrotomy is necessary to gain exposure to the site of the chondral defect. This can usually be accomplished with a limited exposure depending on the location of the defect. The chondral defect is first debrided circumferentially back to a healthy rim of surrounding normal cartilage. Any fibrous tissue or remaining damaged cartilage is removed from the base of the defect with a curette, with careful attention to avoid violating the subchondral bone in order to keep the bone from bleeding. Any punctate bleeding that might occur is controlled with compression sponges impregnated with epinephrine or thrombin. Once the defect has been debrided and conveniently shaped, it is carefully measured for sizing of the periosteal patch. The periosteum is obtained through a small separate incision over the anteromedial tibia just distal to the insertion of the pes tendons. The periosteum from the proximal tibia and distal femur have been shown to be chondrogenic and provide a paracrine effect to chondrocyte growth, as well as providing a water-tight seal to contain the cells as they attach to the subchondral bone and populate the defect. The periosteal patch is harvested 2 mm larger than the lesion and then placed over the defect with the cambium layer down to the bone and secured in place to the surrounding normal cartilage with multiple interrupted absorbable sutures (Fig. 1). Recently, the use of a collagen xenograft membrane instead of periosteal patch is becoming more popular in second-generation ACI. The covered lesion is then sealed with glue usually collagen or hyaluronan secured with fibrin glue or is self-adhering. Finally, expanded chondrocytes are implanted into the closed lesion [29, 33–35]. The MACI technique simplified the second stage, which differs depending on the scaffold used. A mini-open approach can be used to prepare the lesion site, debriding the defect area down to the subchondral bone. Afterward, using a foil template reflecting the size and geometry of the defect, the chondrocyte-loaded matrix is cut to size and fitted into the defect with the cell-loaded surface facing the subchondral bone, and then secured with fibrin glue [36, 37]. Depending on the adhesive characteristics of the grafts, no fibrin glue or sutures are needed (Fig. 2).

Postoperative Rehabilitation

In previous studies about cartilage restoration procedure using ACI, the optimal postoperative rehabilitation protocol (e.g., commencement of motion [ROM], progression of weight-bearing

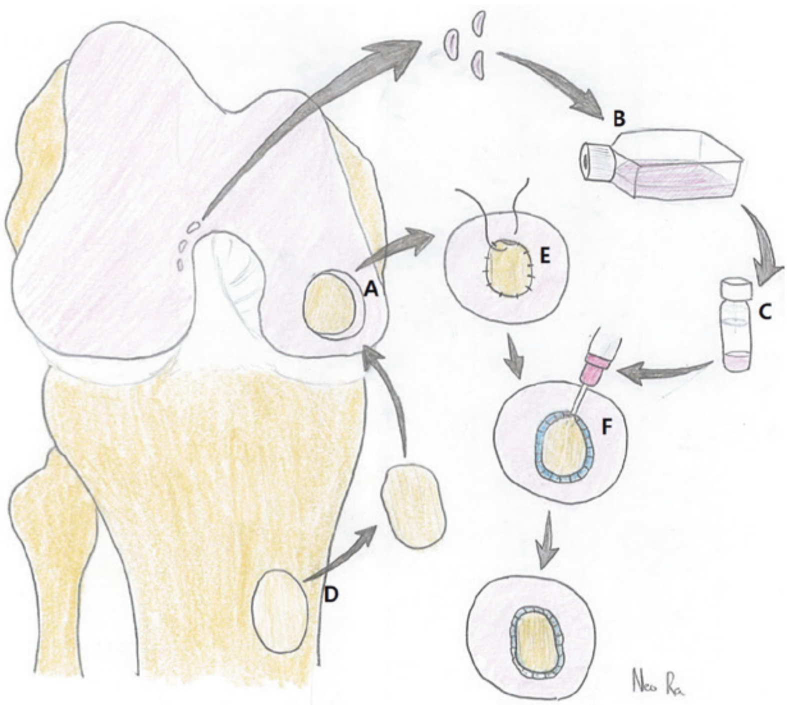

Fig. 1 Autologous chondrocyte implantation (ACI) procedure. **A**: Chondral defect debrided to edge of normal articular cartilage, **B**: Chondrocytes expansion, **C**: Chondrocytes isolation to high chondrocyte density in vitro, **D**: Periosteal graft harvested from anteromedial tibia, **E**: Periosteal patch sutured in place over the prepared defect, **F**: Cultured chondrocytes injected under periosteal patch into defect

[WB] status), or the level of activity that a patient can ultimately regain remains unclear. Nevertheless, it is believed that the goal of rehabilitation is to return the patient to the optimal level of function through a well-controlled gradual and progressive rehabilitation program which emphasizes full motion, progressive weight-bearing, controlled exercises while protecting and promoting the maturation of the implanted autologous chondrocytes. As the repair tissue matures, the rehabilitation process advances with appropriate exercises to condition the lower extremity for strength, flexibility, and proprioception, leading to a return to aerobic and sports activities.

In the early stage (0–6 weeks), the rehabilitation strategies are focused on controlling pain, effusion, loss of motion, and muscle atrophy, and on protecting the transplant by preventing weight-bearing for 4 weeks. Continuous passive motion (0–90°) is allowed within the first week postoperatively. Several basic science studies support the early resumption of ROM for improved cartilage healing [38–41]. Additionally, a standardized early rehabilitation consists of active movement of the ankle to encourage lower extremity circulation; isometric quadriceps, hamstring, and gluteal contractions; cryotherapy to control edema; and education on proficient toe-touch ambulation. In the fourth week, progressive touch-down weight-bearing with crutches is allowed and usually advanced 6–8 weeks after ACI. Subsequently, active functional training can be started if there are no symptoms of overloading, such as pain, effusion, and tenderness. Proprioceptive, strength and endurance exercise and aerobic training are then introduced, aiming to return to a correct running pathway. Although there are no consensus guidelines or criteria on how to allow for safe return to pre-injured sports, the majority of studies only utilized time-based criteria for

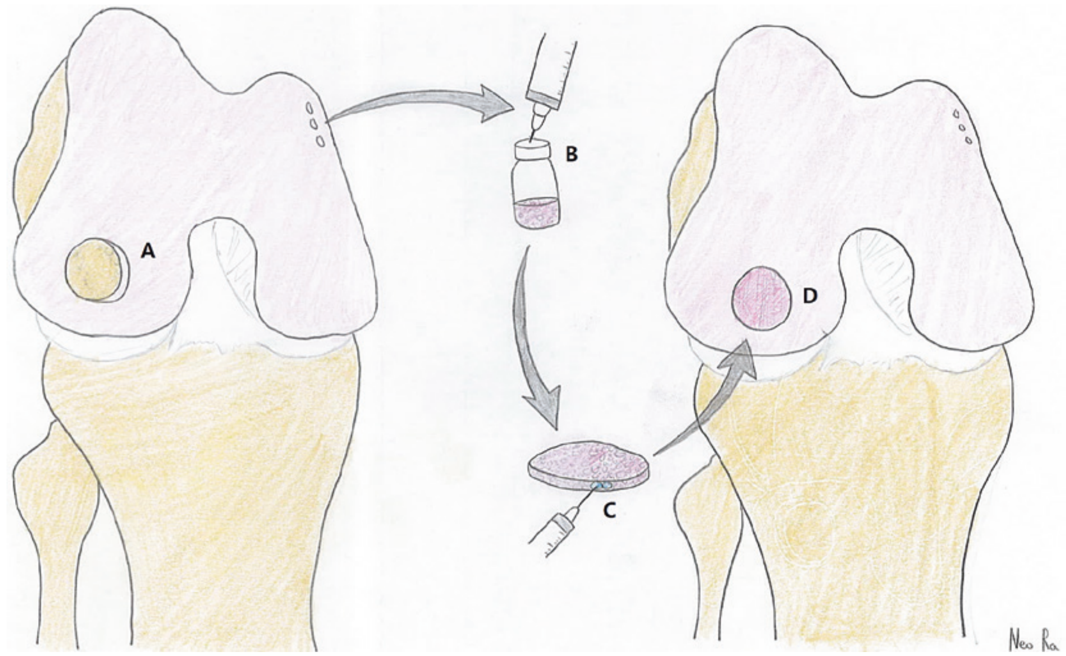

Fig. 2 Matrix-assisted autologous chondrocyte implantation (MACI) procedure. **A**: Chondral defect debrided to edge of normal articular cartilage, **B**: Chondrocytes expansion and isolation to high chondrocyte density in vitro, **C**: Cultured chondrocytes loaded into matrix, **D**: Chondrocyte-loaded matrix fitted into the chondral defect

allowing a return to pre-injured sports. However, Individualized criteria should be utilized in determining to return to pre-injured sports, and individualized criteria should include measures such as the presence of pain, restoration of full ROM, return of functional strength, ability to perform sport-specific movement, and perhaps radiographic evidence of tissue healing at the site of restoration.

Discussion

Cell-based methods, especially ACI and MACI, have resulted in impressive functional, histological, and radiographic outcomes for periods of up to 20 years in several large studies resulting in hyaline-like cartilage formation in larger lesions [18, 26, 36, 42–47]. In the past, microfracture has been considered the first-line treatment option for chondral defects due to its low cost and ability to introduce blood content into the cartilage injured site by bone marrow stimulation. However, the results following microfracture tend to deteriorate from 5 years after surgery, and ACI has recently been spotlighted as a new first-line procedure for articular cartilage injury.

In a 39-month follow-up study of 23 patients known as the first clinical report of ACI, Brittberg et al. reported good or excellent clinical results in 70% of cases (femoral condylar defects had greater rates of healing, nearly 90%) [26]. Subsequently, studies that reported good results of ACI followed. 8-year follow-up study of first-generation ACI for large (mean, 5.33 cm^2), full-thickness, symptomatic chondral defects of the knee showed significant improvements in pain relief and functional outcome [48]. ACI and MACI had been used successfully for large defects up to 22 cm^2 in size [37, 49]. Minas et al. demonstrated that ACI provided durable outcomes with graft survivorship of 71% at 10 years and improved function in 75% of 210 patients with knee osteochondral defects with a mean size of 8.4 ± 5.5 cm^2 [50]. ACI and

MACI were approved by the National Institute for Health and Care Excellence (NICE) in the UK and is recommended as a first-line treatment option in appropriate patients.

In addition, many comparison studies on ACI and other cartilage repair and restoration techniques have been introduced. Many studies reported no difference in results between ACI and other procedures. As a result of performing second-look arthroscopy 2 years after surgery, there was no difference in the International Cartilage Repair Society (ICRS) grading system in three-fourth patients between the microfracture and ACI group, similarly, in biopsy specimens of the repair tissues, no significant difference revealed in hyaline cartilage or fibrocartilage [51]. In comparison study that 41 professional or semiprofessional male soccer players were treated with either second-generation arthroscopic ACI (Hyalograft C) or microfracture for full-thickness osteochondral defects, more than 80% of participants returned to competition in both groups [52]. In comparison between osteochondral autograft transfer and ACI, there were studies that have reported no significant difference [53, 54]. On the other hand, a large prospective study of 831 patients reported a graft survival of about 78% at 5 years and 51% beyond 10 years, as well as improved functional outcomes compared to mosaic plastic surgery. And in this study, 17% in the ACI group had a failed repair and 55% in the mosaicplasty group failed [37, 55]. Also, a recently published systematic review and meta-analysis about the cartilage restoration of the knee suggested that no single technique was unequivocally superior in improving intermediate-term function and pain outcomes and there was no significant superiority of any technique when comparing ACI with osteochondral autograft transfer and ACI across generations. However, it also demonstrated a statistically insignificant trend favoring ACI over microfracture [56].

To put together the previous studies, in conclusion, ACI has the best outcomes in younger patients with a shorter preoperative duration of symptoms and fewer prior surgical procedures. And it is clear that when the chondral defect size is greater than 4 cm^2, ACI shows superior outcomes compared to other cartilage restoration techniques. Despite progress using cell-based therapies like this, there are still several limitations as follows: (1) problems in obtaining sufficient articular chondrocytes to fill defect [57], (2) donor site morbidity [29], (3) uneven distribution of cells within defects, and (4) development of hypertrophy after surgery. So future therapies need to overcome the disadvantages associated with ACI.

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Cartilage Repair with Collagen Gel (ACIC®: Autologous Collagen Induced Chondrogenesis)

Seok Jung Kim, Asode Ananthram Shetty and Yoon Sik Kim

Abstract

Autologous collagen induced chondrogenesis (ACIC) is a single-stage arthroscopic procedure and we developed this method using micro-drilling with atelocollagen injection to the articular cartilage defects. Atelocollagen can provide biocompatibility and a chondrogenic environment for functional cartilage regeneration. We introduce this ACIC techniques in the clinical aspect.

Keyword

Enhanced microdrilling · Atelocollagen · Articular cartilage repair · Arthroscopy

Introduction

When the articular cartilage of the joint discolors or damages enough to cause symptoms, the symptoms often deteriorate over time or develop arthritis [1].

S. J. Kim (✉) · A. A. Shetty · Y. S. Kim
The Catholic University Of Korea, Uijeongbu-Si, Republic of Korea
e-mail: peter@catholic.ac.kr

A. A. Shetty
Institute of Medical Sciences, Faculty of Health and Social Sciences, Canterbury Christ Church University, Canterbury, UK

There is no blood flow in the articular cartilage, and the number of cells that can participate in regeneration is limited [2].

Traditional treatments for joint cartilage damage include arthroscopic debridement, microfracture, osteochondral transfer, and ACI (autologous chondrocyte implantation).

ACI involves increasing the number of cells participating in regeneration for cartilage repair and it has been the most effective standard treatment for cartilage repair since it was introduced clinically in 1994 [3]. However, it has been recognized as being inefficient in terms of time and cost since it requires two operations: 'the harvest' which is the extraction of normal cartilage, and 'transplantation' which occurs after 6 weeks of cell culture.

It is necessary to develope new, effective, and simplified treatments since existing treatments are not suitable for the treatment of cartilage defects that are relatively small or cartilage damage in multiple locations.

The simplest treatment is microfracture, which is relatively effective if the patient is young and the lesion size is small and has satisfactory results in long-term follow-up.

However, in practice patients with joint cartilage damage are most likely to suffer joint cartilage damage in relatively old and varying sizes of lesions, so simple microfracture alone is difficult to produce good results.

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Microfracture is generally a simple and very effective treatment, but in the case of large defect size or multiple lesions, the results are relatively poor [4].

Therefore, recently, new technologies, based on microfracture, have been developed. This involves a new biocompatible scaffold and is being used for clinical use.

AMIC (Autologous Matrix-Induced Chondrogenesis) is an example of an advanced microfracture technique and it has excellent results in short- and medium-term and is an effective treatment for relatively large lesions regardless of age [5].

However, a downside of the AMIC technique is that since a collagen membrane is used, in most cases requires large incisions to transplant it to the lesion. Another limitation is that it cannot be used to treat areas that are difficult to access with an open procedure such as the posterior condyle.

Also if the thickness of cartilage around the defect is thin, or if there is a partial thickness cartilage defect, the thickness of the collagen membrane itself can make it difficult to use.

In the case of a patellar cartilage defect of the knee, the joint is completely exposed through a large midline incision and can be treated only by everting the patella upside down.

These procedural shortcomings can be overcome by using collagen gel in the form of a liquid.

Recently, the ACIC technique was developed by the authors, and following the publication and presentation of basic and clinical results, many researchers have been using these techniques in clinical application [6–8].

ACIC is an acronym for autologous collagen-induced chondrogenesis, which uses atellocollagen gel as a scaffold. Following arthroscopy, microdrilling atellocollagen gel and fibrin mixture is used to fill an articular cartilage defect after drying the lesion and insufflating with CO_2 gas.

Atellocollagen is a highly purified type II collagen that can be acquired via the application of pepsin to porcine skin. In that process, the telopeptide of collagen, which is the immunologically active component is removed, differentiating atellocolagen from collagen.

Collagen is a very natural material since it is the main component of protein in our body and is produced as a part of the musculoskeletal system regeneration. In that process, the reduction of an immune response is considered to be a very important process for perfect regeneration [9].

ACIC is a very effective treatment for articular cartilage defects since it is really a minimally invasive technique and current results are comparable to the AMIC technique, which has been in use for a long period of time.

In the ACIC technique, carbon dioxide is insufflated into the joint so as to secure a space for the injection of the atelocollagen mixture. It is the positive pressure of the CO_2 gas that causes the atelocollagen mixture to stay in a specific defect, while the fibrinogen reacts with thrombin. While the mixture is solidifying, it can make the injected atelocollgen mixture take the role of being an implant.

The fibrinogen and thrombin reaction is commonly used for hemostasis in normal surgical procedures. The process of preparation varies slightly between different manufacturers. For example, the company Baxter advises that with their product fibrinogen should be dissolved by the addition of aprotinin solution and then mixed in a 1 ml syringe. Like the previous mixture, a second batch of thrombin powder should be mixed with calcium chloride liquid before adding this to a 1 ml syringe. After this, two 1 ml syringe are connected by a Y-shaped connector ready for use (Fig. 1).

The company Greencross have made the most advanced product so far. In this product, one syringe is filled with fibrinogen dissolved in aprotinin solution while another syringe is filled with thrombin that has already been dissolved in calcium chloride solution. These two syringes are kept refrigerated until use upon which they are exposed to a warm bath for just 5 min so that thawing can take place (Fig. 2).

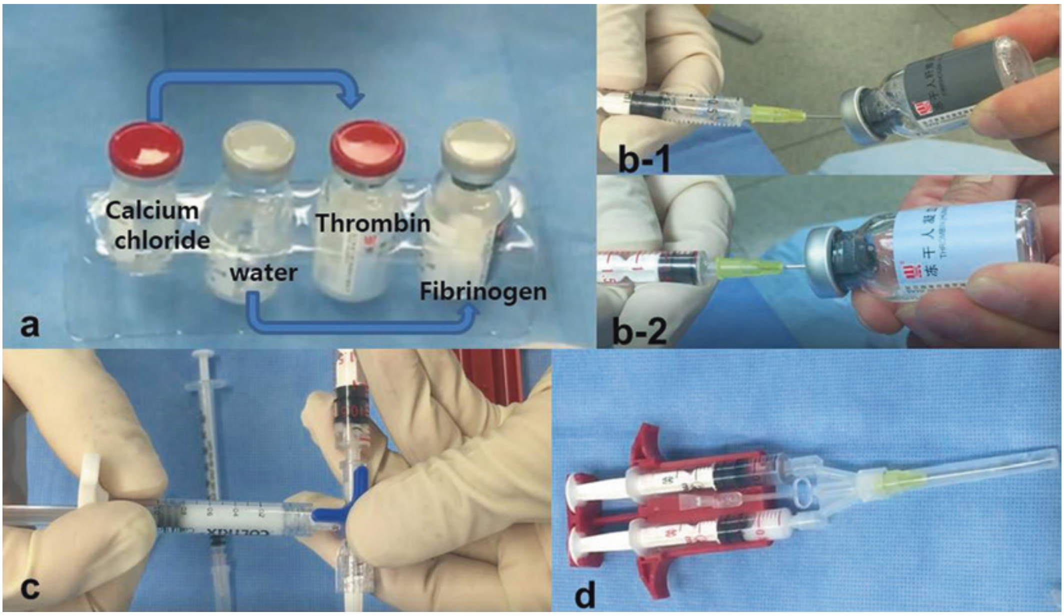

Fig. 1 **a** Four vials of fibrin product: aspirate calcium chloride and inject it to thrombin vial and gently shake to mix; aspirate water and inject it to fibrinogen vial and shake to mix. **b-1** aspirate the mixture from the thrombin vial and **b-2** aspirate the mixture from the fibrinogen vial. **c** mix about 0.8 ml of atelocollagen and 0.2 ml of thrombin. **d** load the 1 ml syringe of fibrinogen and 1 ml syringe of atelocollagen mixture with thrombin to the mixing kit(company provided)

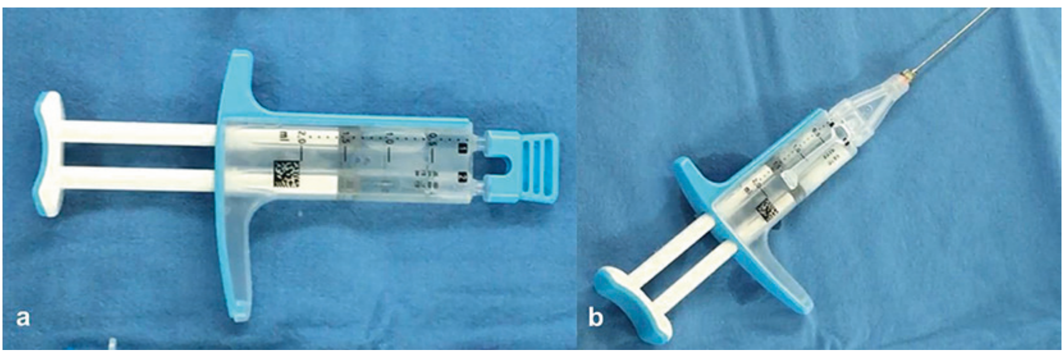

Fig. 2 **a** syringe loaded fibrin product: fibrinogen in number 1 syringe and thrombin in number 2 syringe. **b** mix about 0.8 ml of atelocollagen and 0.2 ml of thrombin. Refilled the mixture to number 2 syringe

For the average Orthopaedic surgeon, the insufflation of CO_2 gas into knee joint is not a familiar clinical skill. Insufflation CO_2 is safe and has been proved by animal testing, continuous injection of CO_2 gas into the vein does not have any harmful effects on the body, something that is supported by the results of laparoscopy surgery. Therefore, this is a reasonably safer surgical procedure on the knee with tourniquet.

Patient Selection

In cartilage regeneration surgery, the correct choice of patients is vital. It is also very important for the cartilage defect to be checked, comorbidity, and patient's overall condition. As well as physical condition, mental condition is another important factor to consider before any surgery.

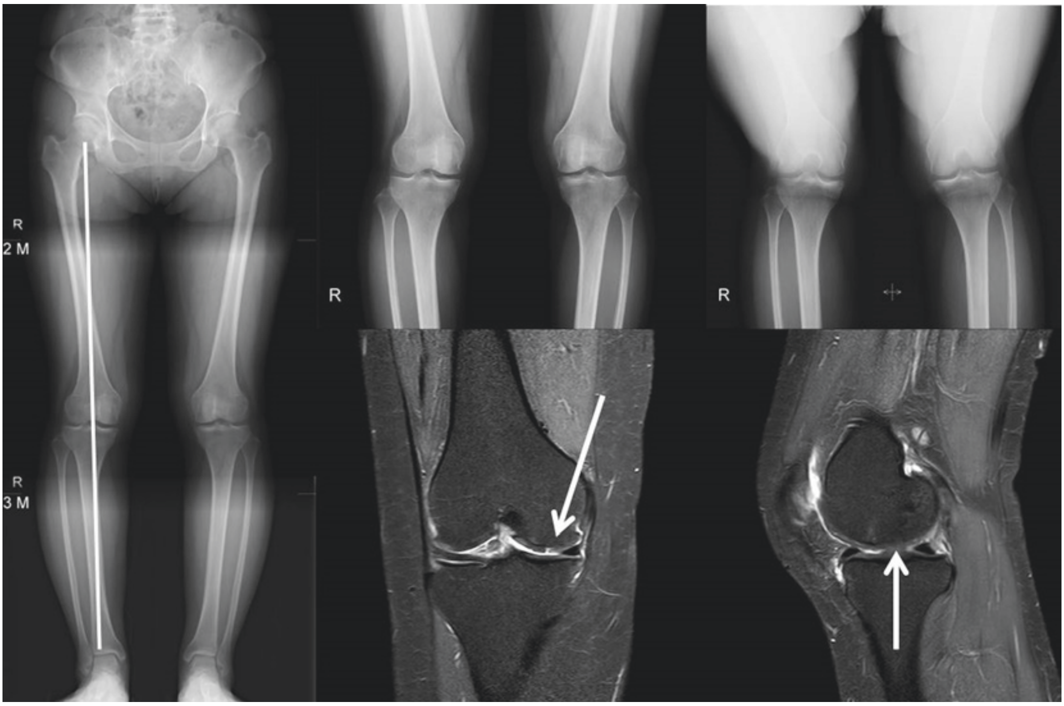

Fig. 3 White arrow indicate cartilage lesion in preoperative imaging studies

With regards to cartilage damage, the following patient criteria are ideal: not serious varus and valgus deformities, only focal damage on cartilage, and that the patient is not overweight.

However, some varus and valgus deformities could be a good indication for operation because it could realign the deformation on the knee through HTO or DFO.

Preoperative Imaging Study

Radiologic study: both knee standing AP, Lateral, skyline view, both lower extremity standing AP (Long leg X-Ray): Fig. 3.

– MRI for evaluation of cartilage status, ligament status, other combined lesion.

Ideal Indication for ACIC

– Clinically significant symptomatic cartilaginous defect. (Outerbrige III–IV)
– Less than 8 cm^2 for a single defect.
– Less than 20 cm^2 for multiple defects.
– A varus or valgus deformity of less than 5 degrees
– Without clinical instability of the knee.

Exclusion Criteria

– Generalized or inflammatory arthritis
– Unable to follow postoperative rehabilitation
– Patellofemoral instability, a history of drug abuse, and psychological disorders
– Active joint inflammation

Atelocollagen and Fibrin Mixture

Atelocollagen is a low-immunogenic derivative of collagen which is obtained by the removal of N- and C-terminal telopeptide components which are known to induce antigenicity in humans [10]. For surgical procedures, it is also possible to use commercially available products for the restoration of cartilage.

The product is normally extracted from porcine skin and after washing and dissolving the porcine skin in HCL or ethanol, and pepsin can be used to remove the telopeptide from collagen. Via the process of salt precipitation and condensation atelocollagen can be acquired [11].

It is well documented that in the acquired atelocollagen product the collagen's structure and nature are well preserved.

Fibrinogen and thrombin products are used to control hemorrhage and, they can be divided into belonging to either of two types according to the compositions (as previously described).

One type is acquired by adding fibrinogen powder to aprotinin solution and dissolving it in this before adding to a 1 ml syringe. In another syringe, thrombin powder is dissolved in calcium chloride solution. Both of these syringes are then connected by a Y-shape catheter (Fig. 1).

The other product comes pre-prepared with each of the two syringes being filled with fibrinogen and thrombin. This goes through the same process of warming as the other alternative and it is ready for immediate use (Fig. 2).

The concentration of fibrinogen and thrombin is similar with each product so there is no problem with using either.

In a 1 ml syringe that is filled with thrombin, take about 0.2 ml of thrombin and discard the rest. By using a three-way catheter, this should be mixed thoroughly with 0.8 ml atelocollagen solution. After this, it should be connected with a 1 ml syringe filled with fibrinogen via a Y-shaped connecter which will provide the preparation necessary for injection (Figs. 1d and 2b).

Surgical Technique

Arthroscopy Setup and Chondral Preparation

The process of preparing the operation room and the patient is the same as with that of normal arthroscopic surgery. Surgical instruments such as a circular curette for debridement of articular cartilage lesion could be helpful for the surgery.

Following injection of normal saline, the condition of the knee should be evaluated by the anterolateral and anteromedial portal. The outflow cannula is located at superolateral or superomedial portal.

Under arthroscopic examination, the size, location, and severity of the lesion are evaluated and if the lesion is found to be appropriate it should be carefully debrided (Fig. 4a).

It is advisable to maintain a stable shoulder of normal cartilage but even if this is not possible a satisfactory cartilage repair layer can be produced by this technique (Fig. 4b).

After performing cartilage defect debridement by curette and shaver, multiple drilling is conducted by a drill bit of diameter approximately 3.5 mm. Normally, drill holes are deeper than 6 mm at an interval of 3 mm (Fig. 4c).

Dry Up and CO_2 Insufflation

Following debridement of the articular cartilage defect, it is necessary that the normal saline infusion is switched off and CO_2 gas should be insufflated through the superlateral or superomedial portal. To introduce CO_2 gas, a special cannula can be used or connected to a normal output cannula (Fig. 5).

Due to the pressure of the injected CO_2 gas, the residual fluid inside the joint can flow out through the portal and can be removed by a suction tube.

The pepared articular cartilage defect can be dried by using cotton buds or small gauze. It is possible to adjust the pressure of CO_2 with most authors citing this as being 20 mmHg and 20 litres/minute.

Injection of Atelocollagen Mixture

The atelocollagen and thrombin mixtures with fibrinogen are connected by a Y-shaped

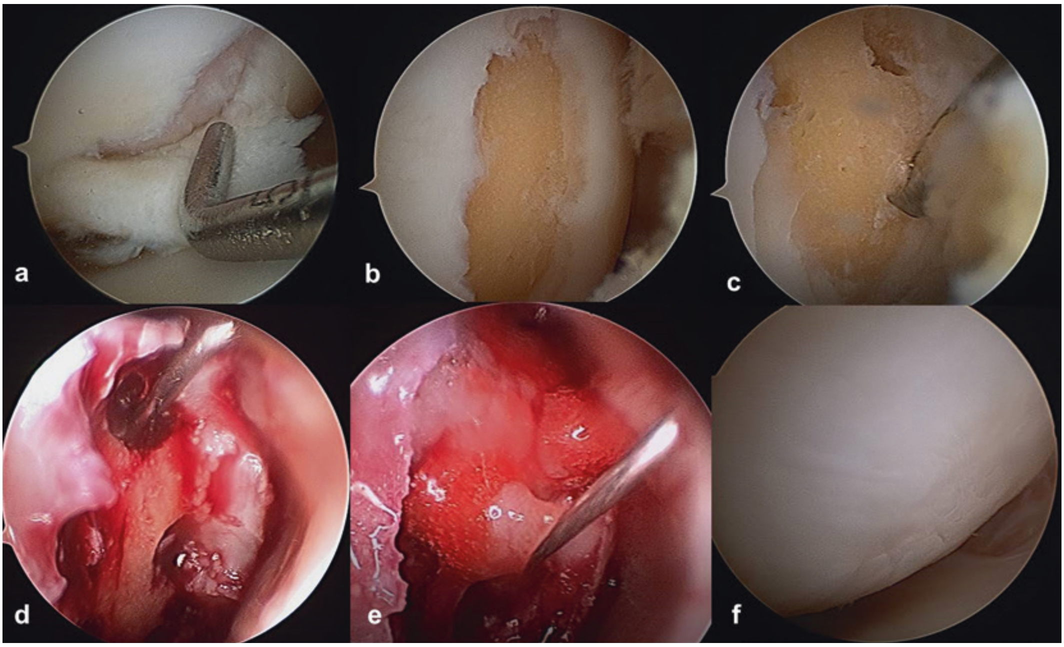

Fig. 4 ACIC procedure: **a** arthroscopic lesion examination. **b** debridement with a good shoulder of lesion. **c** drilling to the defect. **d** injection of the mixture to the upper hole first. **e** cover the defect with atelocollagen mixture. **f** second look arthroscopic finding 2 years after operation

Fig. 5 Operation theater setting for ACIC procedure

catheter and prepared for injection by connecting an 18-gauge spinal needle to the end of the connector.

Due to the CO_2 gas pressure, the atelocollagen mixture that is injected into the lesion, but there is a possibility of overflow. To prevent any overflow, the injection should start from the upper portion of the lesion and drill hole (Fig. 4d, e)

During the injection, joint fluid can obstruct the arthroscopic view; so, in the middle of surgery, a clear view can be secured by aspiration.

After 2–3 min of injection, the injected atelocollagen mixture solidifies and in that time the shape of injected mixture can be contoured by using a nerve freer. The proper distribution of the implant in the articular cartilage lesion should be checked after repetitive motion of flexion and extension of knee, followed by a closure of the skin and completion of the operation.

Rehabilitation

CPM exercises should be started from day 1 after the operation. In the case of tibiofemoral lesion, this begins at an angle of 0–40 degrees, and the time is increased by 20 min to perform 1–1.5 h/time and 3–6 times per day.

Exercise should start with a crutch ambulation and allow for a third of the weight-bearing during the first 6 weeks. This must then be switched to 1/2 of body weight, 2/3 of body weight, and then full weight-bearing at 1–2 weeks intervals to walk without crutches at 3 months after surgery.

For patellofemoral lesion, a brace should be used to limit the flexion angle of the knee. Weight-bearing can be gradually applied using crutches. For the first 2 weeks, allow for 0–40 degrees of joint exercise, and increase the joint exercise by 20 degrees per week. If pain or pressure makes the patient uncomfortable, the exercise angle should be increased slowly. Generally, light exercise is recommended after one year and intensity exercise after 2 years.

Post-operative Follow-up

Since the removal of stitches is conducted 2 weeks after surgery, visit the outpatient clinic to check if there is any pain or discomfort in the knee.

Visit 6 weeks after surgery to determine whether the weight load can be increased during walking on crutches, and examine the condition of the joints by injecting hyaluronic acid.

Stop crutches at 3 months after surgery, check if normal ambulation is possible, and give additional rehabilitation or activity precautions to the patient.

Make sure that light exercise is possible for 6 months after surgery, and be careful not to overdo it. Examine the condition of the joint cartilage by the MRI at 1 year after surgery.

Identifies the condition of the knee and if necessary, attempts to achieve the best surgical condition of the patient through injection therapy or MRI examination (Fig. 4f).

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General Concepts for Patellofemoral Instability

Ki-Mo Jang

Abstract

Patellofemoral instability is a generic term that indicates subluxation/dislocation of the patella, and general symptomatic patellar instability. Patellofemoral instability is one of the most prevalent knee disorders in adolescent and young adult patients and can cause significant functional limitations in daily living activities. The pathophysiology is often multifactorial and complex. The exact understanding of this complex pathophysiology is a top priority in the management of patellofemoral instability.

Keywords

Knee · Patellofemoral instability · Patella · Trochlea groove · Medial patellofemoral ligament

Introduction

The patellofemoral joint is the articulation between the femoral trochlea and the patella. The motion of the patella in the articulation is complex and this joint is vulnerable to several types of instability [1]. The patellofemoral instability is one of the common clinical entities around the knee joint that can cause significant functional limitations [2]. It can occur from morphologic abnormalities within the patellofemoral articulation and alignment as well as from acute traumatic injuries. So far, a variety of non-surgical and surgical treatments have been tried with a varying degree of clinical outcomes [3, 4]. Recently, there have been remarkable advances in understanding the pathophysiology of this condition. Accordingly, advanced treatment modalities have been developed and are expected to provide superior outcomes for the management of patellofemoral instability [1].

Previous studies have shown that an overall incidence of patellofemoral instability is around 5.8 to 49 per 100,000 and it accounts for approximately 3% of all knee injuries and 11% of the musculoskeletal symptoms [1, 3]. The incidence is highest in the second decade and becomes significantly lower after fourth decade [5–7]. Natural history of this condition has shown a relatively high recurrence rate, up to 40% [5, 8]. Although this condition was traditionally thought to occur in sedentary, overweight, adolescent females, recent studies have shown that it also occurs frequently in young male athletic individuals during sports participation and other intensive physical activities [7, 8]. Furthermore, there still remains considerable

K.-M. Jang (✉)
Department of Orthopaedic Surgery,
Anam Hospital, Korea University College of Medicine,
Seoul, Republic of Korea
e-mail: kimo98@hanmail.net

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uncertainty regarding who is at high risk for poor clinical outcomes [5].

A variety of factors are related to the patellofemoral instability including lower limb alignment, ligament laxity, muscular dysfunction, patella alta, increased anterior tibial tuberosity–trochlear groove (TT–TG) distance, and trochlear dysplasia [1, 9, 10]. Understanding of complex pathophysiology in patellofemoral instability requires a thorough knowledge of the biomechanics and anatomy of the patellofemoral joint, taking comprehensive histories, and performing holistic physical examinations.

Classification of Patellofemoral Instability

Patellofemoral stability can be defined as a constraint by passive soft tissue and geometry of bone and cartilage that guide the patella into the trochlear groove and keep it engaged within the trochlear groove as the knee flexes and extends. Whereas patellofemoral instability can be defined as symptomatic deficiency of the passive constraint such that the patella may escape from its asymptomatic position with respect to the femoral trochlear groove under the influence of several displacing forces that could be generated by muscle tension, movement, and/or externally applied forces [11].

– Congenital/traumatic/habitual/obligatory/subluxation/dislocation

The traditional classification of patellofemoral instability includes congenital, traumatic, habitual, obligatory, subluxation, and dislocation [1].

– Acute/chronic patellofemoral instability

Patellofemoral instability is generally classified into acute or chronic on the basis of time duration [12]. Acute patellofemoral instability refers to acute, primary, traumatic episodes in which the patella dislocates. Chronic patellofemoral instability refers to recurrent events of patellar subluxation and/or dislocation.

– Major patellar instability/Objective patellar instability/potential patellar instability

Patellofemoral disorders can be divided into three main groups [13, 14]. Major patellar instability refers to more than one documented patellar dislocation. Objective patellofemoral instability includes patients who have experienced one event of patellar dislocation in the course of their life and who present at least one of the principal factors of instability. This group also includes severe patellar instability such as recurrent or permanent dislocations. Patients with potential patellar instability have never experienced dislocation or subluxation; their main symptom is anterior knee pain and they present at least one of the principal factors of instability.

– Lateral instability/Medial instability/Multidirectional instability

Patellofemoral instability is also described by the direction of instability with a degree of flexion [11]. The most common type is lateral instability when patella escapes in early flexion <45°. In some cases, the patella escapes laterally in flexion >45° (patella displaces from the trochlea suddenly as the knee flexes and the dislocation cannot be prevented by the examiner—referred to as obligatory dislocation in flexion). Rarely, the patella can be dislocated medially (usually iatrogenic). Lastly, there is also a multidirectional instability (lateral and medial).

Related Anatomy and Etiology

Understanding the exact anatomy and basic biomechanics of the patellofemoral joint is critical for clinicians to comprehend how patellofemoral instability occurs and how each treatment can stabilize the joint. The patellofemoral joint consists of the undersurface of the patella and the cartilaginous anterior surface of the distal femur, the femoral trochlear groove. The patella is the largest sesamoid bone located within the quadriceps tendon that has a complex gliding articulation with the femoral trochlear groove [15]. The patella serves as a mechanical pulley to increase the mechanical advantage of the muscle for knee extension while protecting the knee [16]. The depth and steepness of the femoral trochlear groove affect the inherent stability of the patellofemoral joint [17, 18].

Typically, the patella is not engaged in the femoral trochlear groove in full extension of the knee joint. In early flexion, only the distal portion of the undersurface of the patella contacts with the superior portion of the femoral trochlear groove (Fig. 1). Patellofemoral engagement occurs at approximately 30° of knee flexion [19]. Appropriate engagement of the patella on the trochlea is critical to the patellofemoral stability. As flexion of the knee joint increases, the contact area of the patella moves proximally until 90° of flexion and the proximal pole contacts with the distal aspect of the femoral trochlear groove. In this position, the patella is more deeply engaged in the femoral trochlear groove, and further flexion causes the medial facet of the patella to articulate with the lateral edge of the medial femoral condyle and the lateral facet of the patella to articulate with the medial edge of the lateral femoral condyle [1].

Patellofemoral stability is maintained by a combination of local, distant, static, and dynamic factors. Local static stability is provided by bone/cartilage structures of the patella and femoral trochlea and ligaments around the patella such as the medial patellofemoral ligament (MPFL). The bony structures of the patella and trochlea account for most of the patellofemoral joint stability in deeper knee flexion. Local dynamic stability is primarily maintained by the extensor muscles including vastus medialis obliquus (VMO). The main distant static factors are femoral anteversion, knee rotation, and tibial external rotation, while the main distant dynamic factors are the iliotibial band complex, abductors and external rotators around the hip joint, and malrotation of the foot, such as excessive pronation of the subtalar joint, which causes a dynamic valgus force vector that displaces the patella laterally [20–22].

The MPFL is a critical structure for patellofemoral stability as the primary passive stabilizer of the patella especially in early knee flexion (20–30°) (Fig. 2). The medial retinaculum structure of the knee joint consists of three-layered system [superficial layer: deep crural fascia; second layer: superficial medial collateral ligament (MCL), blending fibers of the posterior oblique ligament, and MPFL; deepest layer: deep MCL, meniscotibial and meniscofemoral ligament structures, and joint capsule] [23].

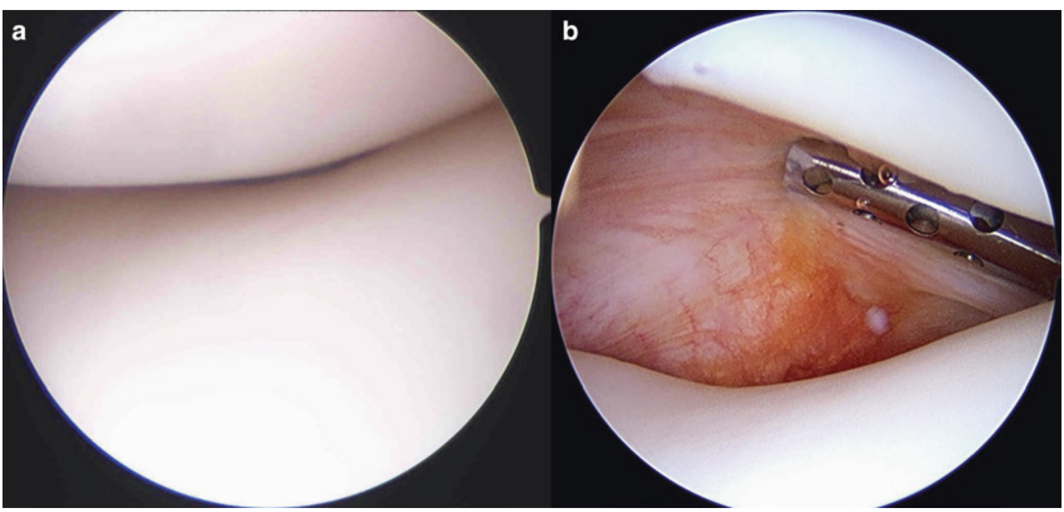

Fig. 1 Arthroscopic view of patellofemoral engagement at early knee flexion. **a** normal articulation. **b** Abnormal lateral tilting of the patella

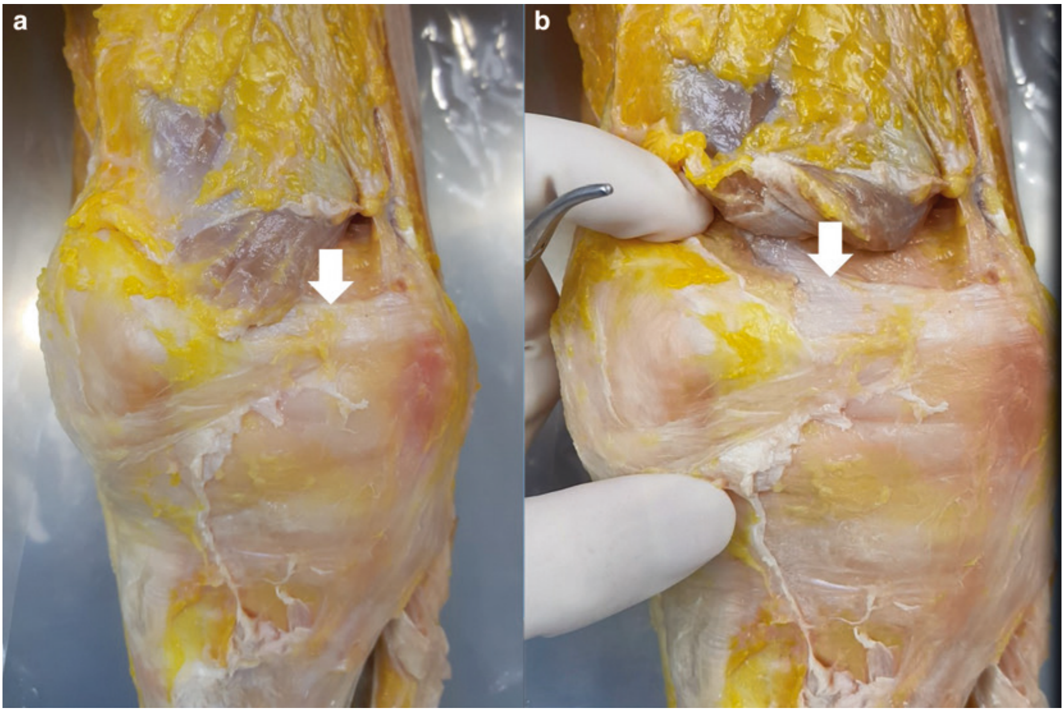

Fig. 2 **a** Cadaveric dissections demonstrating that medial patellofemoral ligament (MPFL, white arrow) attaches on medial patella and undersurface of the vastus medialis obliquus (VMO). **b** Broad insertion of the MPFL (white arrow) on upper half on medial patella (VMO is everted)

The MPFL guides the patella into the trochlear groove and has been reported to provide more than 50% of the medial restraint forces to the patella [1]. The MPFL has femoral and patella attachments. It is well accepted that the MPFL has connections to the deep portion of VMO before it inserts into the upper two thirds of the patella. However, there have been controversies regarding the attachment to the femur. Some authors described the insertion as on the adductor tubercle [24, 25]. Other authors explained it as on or slightly anterior to the medial femoral epicondyle [26–30]. Still, other authors described it as posterior to the medial femoral epicondyle and distal to the adductor tubercle [31–33]. Desio et al. demonstrated that the femoral attachment of the MPFL is 8.8-mm anterior to the line continuous with the femoral posterior cortex and 2.6-mm proximal to a perpendicular line at the proximal aspect of the Blumensaat line [29]. Amis et al. reported that the MPFL is attached to the origin of the medial epicondyle of the femur [34]. Schöttle et al. demonstrated that the femoral attachment site of the MPFL is identified, on a true lateral radiograph, as 2.5-mm distal to the posterior origin of the medial femoral condyle, 1-mm anterior to the posterior cortex extension line, and proximal to the posterior aspect of the Blumensaat line (Schöttle's point) [35]. However, McCarthy et al. reported that Schöttle's point does not correlate with clinical outcomes [36].

The etiology of patellofemoral instability is multifactorial as it involves several abnormal anatomical factors such as patellar alta, trochlear dysplasia, dysplasia of lateral femoral condyle, defective lateral trochlear margin, Shallow trochlear groove, VMO insufficiency, generalized hypermobility, patella hypermobility, increased femoral anteversion, weakness of core and hip abductor, abnormal knee rotation, abnormal Q angle, muscle and soft tissue imbalance, tight lateral soft tissue structure, external tibial torsion, foot hyperpronation, previous surgery, and trauma [1, 37, 38]. Anatomical factors related to patellofemoral instability could be divided into the principal and secondary factors [13]. The principal factors of patellofemoral instability include trochlear dysplasia, abnormal patellar height, and pathological tibial tubercle–trochlear groove (TT–TG) distance, whereas the secondary factors of patellofemoral instability include varus/valgus malalignment, genu recurvatum, pathological femoral/tibial torsion, patellar dysplasia, abnormal pronation of the subtalar joint. The principal factors could be detected through an accurate instrumental evaluation, while the secondary factors could initially be classified clinically and then better detected through specific imaging investigations.

Clinical History and Physical Examination

Careful history taking and physical examination are important in the evaluation and management of patellofemoral instability. Patients with patellofemoral instability sometimes experience anterior knee pain, but episodes of shifting or collapsing (the feeling of the knee ‘‘giving way’’ or ‘‘going out’’) are more prominent complaints [1]. Patient age and gender are relevant to the risk of recurrence. A history of general laxity or dislocation in the patient or family members should be elicited. The number of previous episodes of subluxation or dislocation and the circumstances under which these events occurred should be identified. Any previous management including surgical procedures should also be recorded. Elements of the history that are relevant to the patient's functional status should be obtained, including types of physical activities during daily living, occupation, and sports [3].

Physical examinations for patellofemoral instability should include an evaluation of the overall alignment of lower extremities, dynamic limb alignment in single-leg squat maneuvers, hip and knee rotation, surrounding muscle strength, and generalized ligament laxity [1, 3, 39]. Patellar stability is evaluated by pushing the patella laterally while flexing the knee. Apprehension during lateralization of the patella and the absence of a firm endpoint to lateral translation of the patella during this maneuver suggests previous dislocation and damage to the MPFL. The location of tenderness on the patella or along the MPFL should also be noted. Tracking (J sign), tilt, and mobility of the patella, as well as the presence of crepitus or effusion, should be recorded. With the patient sitting, the examiner should observe the patellar position. Normal patella is centered within the trochlear groove and face forward. When the patella is located in a high and lateral position, it is described as "grasshopper eyes," as they appear to look up and over the examiner's shoulder [12]. Assessing patellar tilt will allow checking for excessively tight lateral soft tissue restraints. Generally, a posterior directed force on the medial patella allows the lateral patella to reach a neutral or horizontal position in the sagittal plane. Inability to elevate the lateral patella to this plane indicates excessively tightness of lateral retinaculum [12]. Mobility of the patella is tested with the knee joint flexed to 30°. Normally, medially and laterally directed forces displace the patella no more than half of its width [40]. The patellar grind test is performed by applying direct pressure on the patella and manually displacing the patella medially, laterally, proximally, and distally in the femoral trochlear groove. If there is a pathological condition in the patellofemoral joint, this maneuver provokes anterior knee pain. The Q (quadriceps) angle is defined as the angle between lines joining the anterior superior iliac spine, the center of the patella, and the tibial tubercle. It is normally between 8° and 10° in males and between 15° and 20° in females. It is important to remember also that this is strictly a static measurement and has limitations in assessing a dynamic joint [41]. The factors related to the Q angle are genu valgum, external tibial torsion, a laterally positioned tibial tuberosity, degree of knee flexion, isometric contraction of the quadriceps muscle, and increased femoral anteversion. Any factor increasing the Q angle increases the laterally directed force on the patella, thereby predisposing the patella to instability [1].

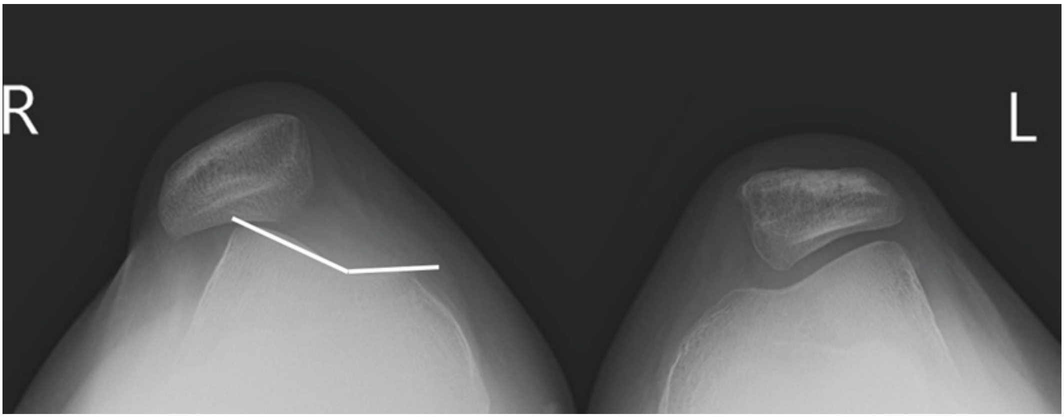

Fig. 3 The Merchant view of both knee joints. Lateral patellar subluxation and increased Sulcus angle (151°) are identified on right knee joint

Imaging

Radiographs

The radiographs for assessing the patellofemoral instability include an anteroposterior, lateral, and Merchant view of the knee joint. In addition, a full-length weight-bearing radiograph is necessary for the standing position for accurate measurement of the limb alignment. It is important to bear in mind that a significant amount of information could be achieved from these radiographs; however, they are limited in that they provide static images of a dynamic joint [12]. The patellar height (patella alta or baja) can be measured on the lateral radiograph with the knee flexed to 30° based on the Insall–Salvati ratio, modified Insall–Salvati index, Caton–Deschamps index, or Blackburne and Peel index [42–45]. In addition, trochlear depth can also be assessed on the lateral view. Dejour et al. classified femoral trochlear dysplasia into four types based on observation of the trochlea on the lateral radiographs [46]. This classification can be useful for quantifying the degree of femoral hypoplasia.

- Dejour's classification of trochlear dysplasia
- Type A: On lateral radiographs, the line of the femoral trochlear groove is seen to intersect the anterior border of one of the condyles (the trochlear groove is flush with the facets) (“crossing sign”).
- Type B: On lateral radiographs, it is possible to observe both the “crossing sign” and the “supratrochlear spur”.
- Type C: On lateral radiographs, it is possible to observe both the “crossing sign” and the “double contour sign” which represents a hypoplastic medial femoral condyle.
- Type D: On lateral radiographs, all three signs of dysplasia are present (“crossing sign”, “double contour sign”, and “supratrochlear spur).

The Merchant view is necessary to assess the congruence angle, the sulcus angle, articulation and reduction of the patellofemoral joint, and the presence of osteochondral fragments (Fig. 3). The sulcus angle is defined as the angle formed between lines joining the highest points of the bony medial and lateral condyles and the lowest bony point of the intercondylar sulcus (normally averages 138°) Femoral sulcus angle and increased patella facet cartilage volume in an osteoarthritic population [47]. Increasing sulcus angles may indicate trochlear dysplasia. The congruence angle is defined as an angle between a bisecting line of the sulcus angle and a line drawn from the center of the femoral trochlea to the lowest portion of the patella. It defines the relationship of apex of patella to bisected femoral trochlea. Medial angles are negatively reported and lateral angles are reported positively (Angles > +16° denote lateral subluxation of the patella) [48].

Computed Tomography (CT) Scans

CT is useful in better assessing the sulcus angle, congruence angle, trochlear depth, patellar tile, femoral/tibial torsion, and the TT–TG distance. The TT-TG distance is the offset of the tibial tuberosity relative to the true trochlear groove and is obtained from superimposing the two appropriate axial CT images. It is very helpful in quantifying the amount of lateralization of the tibial tuberosity. However, the amount of lateralization of the tibial tuberosity that may contribute to actual dislocation varies among studies. Alemparte et al. studied healthy volunteers and demonstrated that normal values for TT–TG were 13.6 ± 8.8 mm [49]. Dejour et al. reported that the TT–TG in the control group was 12.7 ± 3.4 mm [14]. The TT–TG greater than 20 mm is believed to be a pathological condition and a good candidate for medialization of the tibial tuberosity [1, 12, 50].

Magnetic Resonance Imaging (MRI)

MRI is also indicated in the acute setting to rule out osteochondral injury, which is an indication for early surgical management. The characteristic MRI findings in acute patellar dislocations include hemarthrosis, focal impaction with bone bruise in the lateral femoral condyle, osteochondral injuries to the medial facet of the patella, and medial retinacular injuries [51]. The bone bruises on the medial patella and the lateral femoral condyle ("kissing lesion") result from the lateral patellar dislocation and relocation [52] (Fig. 4). MRI is also useful for detecting MPFL injuries. Injury of the MPFL is well visible on both sagittal and axial T2-weighted images [53].

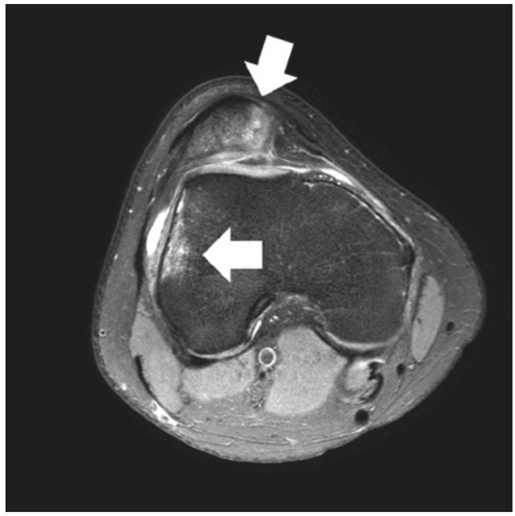

Fig. 4 The bone bruises (white arrows) on the medial patella and the lateral femoral condyle ("kissing lesion"), which result from the lateral patellar dislocation and relocation, are identified on MRI

Treatment

Nonoperative Treatment

The management of patellofemoral instability often depends on the presence or absence of predisposing risk factors [9]. Over the past two decades, a variety of studies and reviews have been published on nonsurgical and surgical treatment of patellofemoral instability [4].

Patellofemoral instability can often be treated successfully without surgical treatment. In general, surgical management is avoided in patients with only one subluxation or dislocation episode, as most of these patients do not experience recurrent dislocation. In acute patellar dislocations, the goals of early treatment are to immobilize, reduce swelling around the knee joint, strengthening the surrounding muscles, and improve knee range of motion. There is still no consensus on the type and duration of immobilization after an acute patellar dislocation. Options for initial immobilization include casting, splinting, or bracing. Patients may be immobilized in nearly full extension of the knee joint. In a long-term study of nonoperative treatment, patients treated conservatively in casts for 6 weeks had a lower risk of recurrent dislocations but higher rates of stiffness. In contrast, patients treated with just a patellar brace had 3 times the risk of redislocation [54]. Several studies have compared early surgical intervention with nonoperative management of first-time patellar dislocations. Buchner et al. reported that there was no significant difference between the surgically and conservatively treated groups regarding redislocation, activity levels, and clinical outcomes in 8-year follow-up [55]. Palmu et al. also demonstrated that there was no significant difference in the subjective outcome, recurrent instability, function, or activity scores in a prospective randomized study [56]. Arnbjornsson et al. followed 21 patients with a history of bilateral patellar dislocations for a mean of 14 years. One lower extremity was treated operatively, whereas the other side was treated nonoperatively. In long-term follow-up, the patients showed worse arthritis and increased risk of redislocation in operated sides [57].

Functional rehabilitation is the mainstay of nonoperative management with a focus on gait, core stability, stretching of the lateral retinaculum, hamstrings, quadriceps, Achilles tendon, and iliotibial band, and strengthening of quadriceps and VMO [1, 3]. Physical therapy for patients with patellofemoral instability should include closed-chain strengthening of the quadriceps, VMO, and gluteal musculature [58, 59]. Strengthening of the quadriceps and VMO brings the patella medially into the femoral trochlear groove. Closed chain exercises for the gluteal muscles increase the external rotation and abduction of the femur and as such decrease the dynamic Q angle during the gait cycle [39, 60].

Patellar brace, taping, or functional mobilization could be a useful method in the management of patellofemoral instability. Patellar taping was introduced by McConnell to improve patellofemoral tracking [61]. Some studies showed that patellar taping could control excessive patellar motion during therapy and serves to activate the VMO earlier than the vastus lateralis [62, 63]. The advantage of the brace is that it could stabilize and prevent the patella from dislocation, especially in the first 30° of flexion. Becher et al. reported that there was a significant decrease in patellar tilt angle and patellar height ratio with the use of a brace [64]. Weight loss is another effective way to reduce patellofemoral loads [1].

Surgical Treatment

If there is no clinical improvement following nonoperative management, operative treatment may be indicated. Indications for surgical management depend on patients' pain and function. In many cases, patients do not complain of symptoms at rest, whereas they have significantly limited function due to apprehension [65]. Therefore, the risk of recurrence of patellofemoral instability is an important factor for consideration of surgical management [3]. Other indications for surgical treatment include a symptomatic osteochondral loose body or cartilage lesions (Fig. 5). A survey for physicians in the National Football League team indicates that most do not recommend immediate surgical management without a loose body [66]. However, if the patient has continued apprehension or repetitive dislocations, surgical management is typically recommend based on the high risk of recurrence.

Surgical management of patellofemoral instability should be selected with respect to the patient's age and activity level as well as the condition of the joint. It must be directed at correcting injured structures to recreate normal anatomy without causing excessive abnormal loads or abnormal constraint on the articular cartilage that can result in secondary arthritis

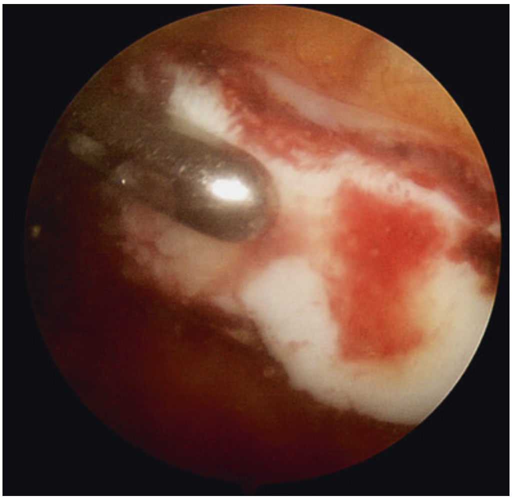

Fig. 5 Arthroscopic view of the osteochondral loose body held using a grasper forcep in a case of acute patellar dislocation

[3]. Traditionally, there are two types of surgical approaches for patellofemoral instability: proximal realignment and distal realignment. Trochleoplasty is rarely indicated, particularly in young patients, as the long-term results are not known [1].

– Proximal realignment

Proximal realignment procedures include Primary repair and reconstruction of MPFL, medial imbrication and advancement of VMO, lateral retinacular release. The purpose of these procedures is to correct the position of the patella by manipulating the soft tissues (most importantly, the MPFL) proximal to the inferior patellar pole.

– Distal realignment

Distal realignment procedures include anteromedial tibial tuberosity transfer and tibial osteotomy. The purpose of these procedures is to modify the position of the patella by the transfer of the tibial tuberosity.

Summary

Patellofemoral instability can cause significant pain and functional disability in daily living activities and sports participation. Various factors can predispose the patella to instability, such as ligament laxity, abnormal alignment of the lower limb, increased anterior TT–TG distance, patella alta, muscle imbalance, trochlear dysplasia, and trauma. Patellofemoral instability is a difficult condition to manage, and the anatomy of the patellofemoral joint and its static and dynamic stabilizing structures must be taken into account. Recently, there have been remarkable advances in understanding the pathophysiology of patellofemoral instability. Understanding this complex pathophysiology of patellofemoral instability is critical to the proper management of this condition. In many cases, the first dislocation can be managed successfully with nonoperative management including patient education and tailored physical therapy. However, with an increased risk of recurrence, surgical treatment should be considered. Surgical treatment should be individualized to recreate the normal anatomy of the joint and recover function.

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Surgical Reconstruction of the Medial Patellofemoral Ligament

Sung-Hwan Kim and Hyun-Soo Moon

Abstract

The medial patellofemoral ligament (MPFL) is the primary soft-tissue stabilizer of the patella, acting as a checkrein to lateral patellar displacement. Considering the growing awareness regarding the anatomy and biomechanics of MPFL, numerous studies have been conducted on surgical reconstruction of the MPFL. However, while MPFL reconstruction has been recognized as an established surgical procedure for recurrent patellar dislocation with overall favorable clinical outcomes, there are numerous debatable issues that have not yet been resolved. These include a lack of consensus regarding surgical indications, graft selection, graft tensioning, surgical technique, and indications for other surgical procedures. Since the cause of patellofemoral instability is multifactorial and there is still no conclusive evidence that a particular surgical option is superior to others, thorough evaluation of proper patient selection and individualized surgical planning is required to yield successful outcomes.

Keywords

Medial patellofemoral ligament (MPFL) · MPFL reconstruction · Recurrent patellar dislocation · Patellar instability

S.-H. Kim (✉) · H.-S. Moon
Arthroscopy and Joint Research Institute, Yonsei University College of Medicine, Seoul, Republic of Korea
e-mail: orthohwan@gmail.com; orthohwan@yonsei.ac.kr

S.-H. Kim
Department of Orthopedic Surgery, Gangnam Severance Hospital, Yonsei University College of Medicine, Seoul, Republic of Korea

H.-S. Moon
Department of Orthopedic Surgery, Hallym University Sacred Heart Hospital, Hallym University College of Medicine, Anyang, Republic of Korea

Recurrent patellar dislocation is a debilitating condition, which could be associated with significant morbidities such as chondral injury and subsequent patellofemoral osteoarthritis. Reportedly, the incidence of articular cartilage injury was 95% among knees with initial patellar dislocation and 96% among knees with recurrent dislocation [1, 2]. This usually presented with anterior knee pain, swelling, limited range of motion, and frequent 'giving-way' episode, which subsequently resulted in the considerable functional limitation of daily activity [3]. Atkin et al. reported that 58% of the patients with acute patellar dislocation showed limitation of strenuous activity at 6 months after the injury despite the standardized rehabilitation program [3]. The reported incidence of patellar dislocation is 5.8 per 100,000 [4]. Along with the high incidence rate, the overall recurrence rate after acute patellar dislocation ranges from 29 to 71% [4–6].

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Since multiple factors, such as soft-tissue stabilizers, osseous structures, and lower limb alignment, contribute to patellofemoral instability, numerous surgical treatments based on the underlying pathophysiology have been proposed. Of those, the incidence of medial patellofemoral ligament (MPFL) injury was reported to be 96% in patients with initial acute patellar dislocation [7]. The MPFL is the primary soft-tissue stabilizer against lateral displacement of the patella. If the MPFL is deficient or lax, the patella is at risk of lateral translation and displacement [8, 9]. Accordingly, numerous studies have been conducted on surgical reconstruction of the MPFL and many systematic reviews have demonstrated that MPFL reconstruction is an effective surgical procedure with remarkable outcomes [10–12].

Anatomy and Biomechanics

Restoration of the MPFL has been recognized as an established surgical procedure when the primary pathologic feature of patellofemoral instability results from soft tissue problems rather than the osseous problems [13, 14]. However, it was reported that non-anatomical restoration of the MPFL would result in non-physiological force and pressure on the medial patellofemoral cartilage, which may lead to a worse clinical results [15]. Therefore, a correct understanding of the MPFL anatomy and biomechanics is crucial for the planning of surgical treatment, functional restoration of the MPFL, and subsequent good clinical outcomes.

The MPFL was first described by Warren and Marshall in 1979 in their anatomic cadaveric study as transverse fibers within layer II of the medial side of the knee extending from the medial epicondyle of the femur to the patella [16]. Subsequently, numerous studies regarding the anatomy and biomechanics of the MPFL have been conducted. Previous anatomical studies have revealed that the MPFL is 45–64 mm in length, 8–30 mm in width, and has a narrow central portion, thus resulting in an hourglass shape [17–20]. Although MPFL fibers have been reported to vary in their width and in the percentage of attachments, the ligament usually has a smaller femoral origin (9–17 mm) compared to the fan-shaped patellar attachment (19–29 mm) [20–22]. The femoral attachment was reported to be located 9.5 ± 1.8 mm proximal and 5.0 ± 1.7 mm posterior to the center of the medial femoral epicondyle, while the patellar attachment was reported to be located at 27 ± 10% from the upper end of the medial side of patella [23]. Since the position of the MPFL has been described as highly variable in the literature, Aframian et al. conducted a systematic review regarding the origin and insertion of the MPFL [20]. Their analysis of 33 papers on the femoral origin of the MPFL and 29 papers on its patellar insertion suggested that the MPFL originated from a triangular space between the adductor tubercle, medial femoral epicondyle, and gastrocnemius tubercle and was inserted into the superomedial aspect of the patella (Fig. 1) [20]. Due to the variability in the anatomy of the MPFL, graft placement during MPFL reconstruction should be patient-specific and based on the knowledge of previous anatomical studies.

In terms of biomechanics, MPFL is still recognized as the primary soft-tissue stabilizer of the patella contributing to 50–60% of the restraint, even though the importance of

Fig. 1 Postoperative computed tomography image of the knee after MPFL reconstruction surgery. The femoral insertion of the MPFL graft is located in a triangular space consisting of the adductor tubercle, medial femoral epicondyle, and gastrocnemius tubercle (arrow). The patellar insertion of the graft is located at the superomedial aspect of the patella (two arrowheads)

the medial patellotibial ligament and the medial patellomeniscal ligament has also been emphasized recently [24, 25]. The MPFL experiences maximum loads during the first 30° of flexion, acting as a checkrein to lateral displacement of the patella in conjunction with the vastus medialis obliquus, ensuring that the patella is placed in the trochlea during early flexion [26–28]. When the knee flexion exceeds approximately 30°, the femoral trochlea contributes more to patellofemoral stability. The mean failure load for the MPFL was 178 ± 46 N [25]. Similarly, Mountney et al. reported that the mean tensile strength of the MPFL was 208 ± 90 N at 26 ± 7 mm of displacement [8]. In regard to isometry, previous biomechanical studies have revealed that correct placement of femoral fixation would produce isometric adjustment of the graft [27–32]. Stephen et al. reported that a change of only 5 mm in the proximal–distal placement of the graft would cause significant loss of isometry [31]. Recently, in an in vivo laboratory study, Song et al. showed that the MPFL is a complex of functionally varying fibers consisting of taut as well as slack fibers throughout the range of knee motion, which represents a theoretical background for anatomic double-bundle MPFL reconstruction [32].

General Considerations Before Surgical Treatment

Since the cause of patellofemoral instability is multifactorial, surgical treatment should be individualized according to the underlying pathophysiology. Although surgical indication for MPFL reconstruction is still debatable, recurrent patellar instability with more than two dislocation events and failure of conservative treatment are the generally accepted surgical indications [33, 34]. Furthermore, while considering other etiologic factors simultaneously, isolated MPFL reconstruction is recommended for patient with a tibial tuberosity–trochlear groove distance<20 mm, no excessive increment in the patellar height (Caton-Deschamps index <1.2), and normal or grade A trochlear morphology [34, 35].

Graft Preparation

Since numerous surgical techniques for MPFL reconstruction have been proposed, there has been no consensus regarding the choice of the graft source. Commonly used autograft sources include the semitendinosus, gracilis, patellar tendon, adductor magnus, and quadriceps tendon. The semitendinosus, tibialis anterior, and patellar tendons are utilized for allografts. Furthermore, synthetic materials are also used as graft sources. In a systematic review, Fisher et al. reported that the semitendinosus autograft was the most commonly used graft constructs (28.4%) [36]. Recently, in a systematic review involving 31 previous studies to determine the influence of graft source and configuration, Weinberger et al. reported that a double-limb graft configuration provided superior surgical outcomes in terms of stability and clinical scores [37]. In addition, they suggested that the autograft tendon might be associated with favorable patient-reported outcomes, while revision rates were not different among graft sources [37]. However, in a systematic review of 45 studies, McNeilan et al. suggested that autografts were not superior to allografts or synthetic grafts for isolated reconstruction of the MPFL [38]. They suggested that graft selection should be based on the surgeon's preference, comfort, and prior experience. Due to the paucity of properly designed randomized controlled trials involving direct comparison, there is still no conclusive evidence that a particular surgical modality is superior to others.

The knee flexion angle for appropriate graft tensioning has also been a topic of debate. It has been reported to range widely from 20° to 70° [39–45]. In terms of anatomometricity, Schöttle et al. suggested that tensioning the graft should be performed at 30° of flexion [43]. Since it has been reported that the MPFL experiences maximum loads during the first 30° of flexion, [26–28] several authors have suggested that tensioning the graft at approximately 30° of flexion would be appropriate [28, 42–45]. On the other hand, in a recent biomechanical study, Lorbach et al. suggested that graft fixation at 60° of flexion was able to restore the patellofemoral contact pressure most accurately when compared with the native knee [46]. They suggested that femoral fixation of the graft at 60° of knee flexion would prevent over-tensioning of the graft.

The application of adequate tension during graft fixation should also be considered. Several studies have suggested methods for tensioning the graft during MPFL reconstruction. Ellera Gomes used a dynamometer to adjust adequate tension, suggesting that the ideal point for fixation was when the dynamometer showed a displacement of <5 mm during flexion and extension [47]. Nomura et al. utilized a tension spacer to apply a minimum amount of tension (approximately 0.5 kgf) to the graft [48]. Feller et al. applied tension to the graft manually using an anatomic landmark, adjusting the graft tension to allow lateral patellar glide of one quadrant at 20° of knee flexion [39]. A biomechanical study by Beck et al. provided objective evidence of recommended tension during MPFL reconstruction [49]. They reported that low tension (2 N) would be adequate to stabilize the patella and would not increase the patellofemoral contact pressure, whereas higher loads (10 and 40 N) would result in significantly increased patellofemoral contact pressure. Regardless of the applied method, overtension should be avoided during graft tensioning.

The Method Preferred by the Authors

Numerous operative techniques for MPFL reconstruction have been proposed to date, but there is no conclusive evidence that a particular surgical modality is superior to the others [10]. The surgical technique preferred by the author for MPFL reconstruction is described below.

The patient was positioned on an operating table in a supine position. Under anesthesia, physical examination was performed to assess mediolateral displacement of the patella at 0–30° of knee flexion to examine patellar stability and retinacular tightness before the tourniquet was inflated. Diagnostic arthroscopy was performed to evaluate the status of patellofemoral articulation and to identify any associated intra-articular pathology. Cartilage lesions of the patellofemoral joint and the presence of loose bodies should be thoroughly evaluated and lateral retinacular release can be performed when indicated.

The authors preferred using a gracilis autograft as a graft source. An oblique anteromedial incision was made at the level of the tibial tubercle to harvest the gracilis tendon. After exposing the sartorius fascia, tendons were identified and released from the proximal muscular attachment using an open tendon stripper at 90° of knee flexion. Subsequently, two-strand graft preparation with the harvested tendon was performed, whipstitching approximately 25 mm portion from both ends of the tendon. The graft was generally 5–6 mm in diameter.

A longitudinal incision was made along the superomedial side of the patella preserving the joint capsule underneath. Deeper dissection was performed to expose the medial margin of the patella between layers II and III and two suture anchors were fixed at mid-height and proximal 1/3 height of the medial margin of the patella (Fig. 2A). An additional vertical incision of 3 cm length was made over the palpable prominence of the medial femoral epicondylar area of the knee. Care was taken to avoid injuring the branches of saphenous nerve. After exposing the MPFL origin between the medial epicondyle and the adductor tubercle, a temporary Kirschner wire was inserted as a guide for femoral insertion (Fig. 2B). To confirm the appropriate placement of the Kirschner wire, a true-lateral fluoroscopic image using a C-arm was obtained [50]. As described by Schöttle et al., the position of the guide pin was adjusted to ensure its placement just anterior to the posterior cortex extension, just distal to the posterior origin of the medial femoral condyle, and just proximal to the posteriormost point on the Blumensaat line [51]. After confirming the correct placement of the guide pin (Fig. 3), a femoral tunnel was made according to the diameter of the prepared graft tendon, facing forward and upward by approximately 10°. Subsequently,

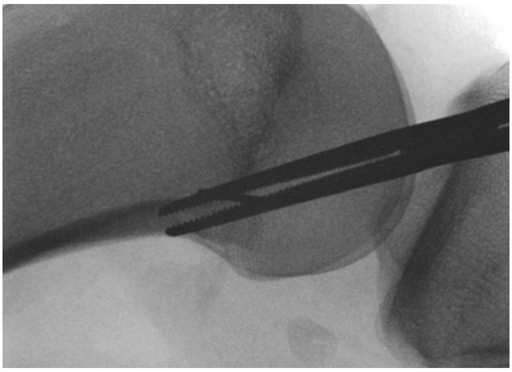

Fig. 3 Intraoperative localization of the femoral insertion point, as described by Schöttle et al. [51]

the graft tendon was passed through the two different incisions, ensuring that the loop site (the middle portion of the tendon) was placed on the patellar side and both the ends of the tendon were placed on the femoral side (Fig. 2C). The loop site of the graft tendon was fixed with two suture anchors on the superomedial edge of the patella (Fig. 2D). After passing a suture whipstitched at the ends of the graft tendon through the guide pin, the guid pin was pulled out at the lateral side of the thigh, ensuring that both the ends of the tendon were inserted into the femoral tunnel. After the cycling preconditioning process, graft tension was adjusted to allow lateral patellar glide of 1/4 to 1/2 quadrant at 30° of knee flexion. Finally, a bioabsorbable interference screw was inserted into the femoral tunnel. The graft loop area, which was secured at the superomedial border of the patella, was augmented with 1-0 Vicryl®sutures. At the end of the surgical procedure, restoration of congruent articulation of the patellofemoral joint was confirmed by arthroscopic examination (Fig. 4).

Clinical Outcome

Surgical reconstruction of the MPFL has generally shown favorable results. In a prospective single-clinic series of patients treated with MPFL reconstruction, Enderlein et al. reported

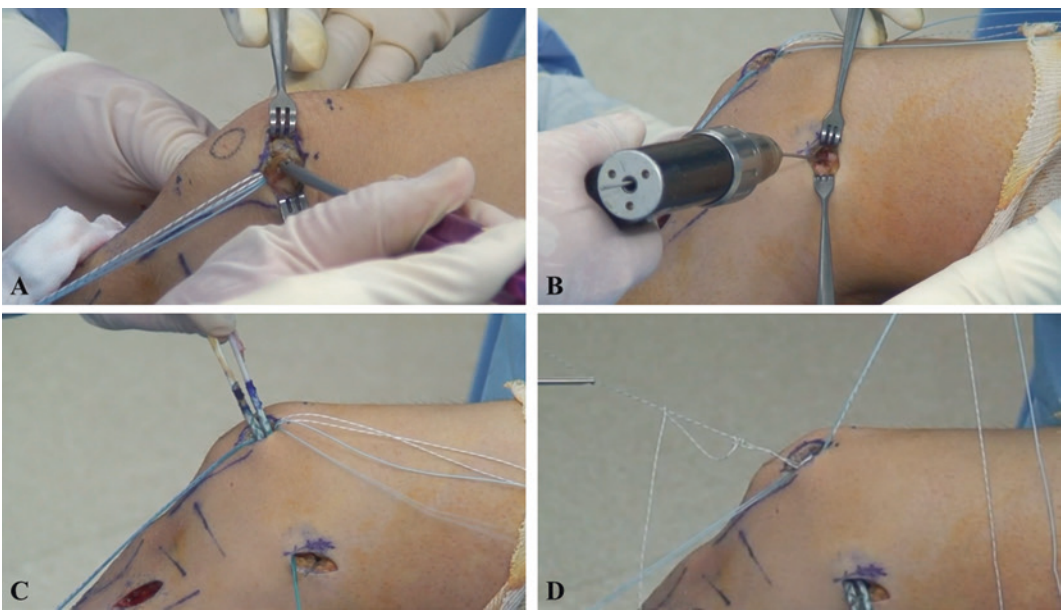

Fig. 2 (**A**) Two suture anchors were fixed at mid-height and proximal 1/3 height of the medial margin of the patella. (**B**) Temporary Kirschner wire was inserted as a guide for femoral insertion at the location described by Schöttle et al. [51] (**C**) The graft tendon was passed through the two different incisions ensuring that the loop site was placed on the patellar side and both the whipstitched ends of the tendon were placed on the femoral side. (**D**) The loop site of the graft tendon was fixed with two suture anchors on the superomedial edge of the patella

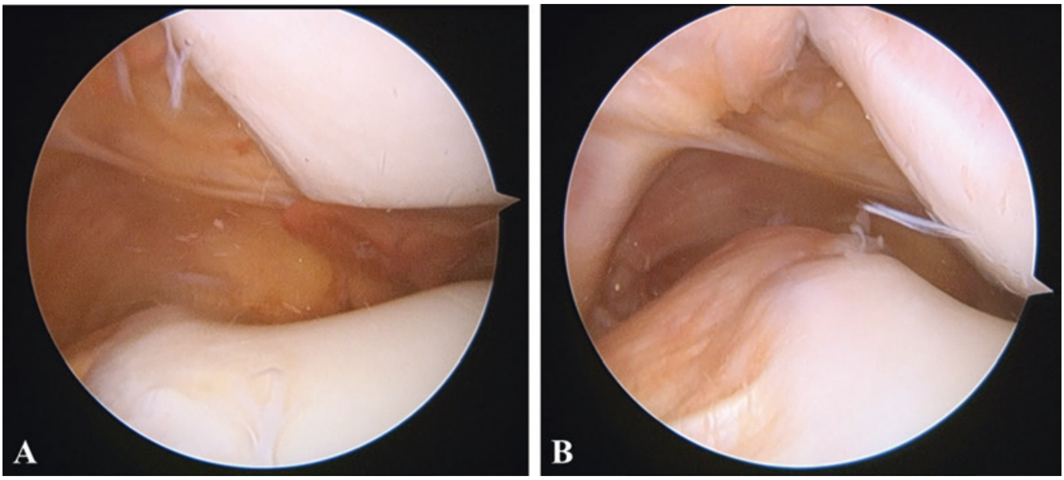

Fig. 4 Arthroscopic findings before and after MPFL reconstruction of the right knee. (**A**) Before the reconstruction procedure, the patella was subluxated to the superolateral side. (**B**) After MPFL reconstruction, congruent patellofemoral articulation was restored

that reconstruction with a gracilis autograft tendon resulted in consistent restoration of patellar stability and improvement of knee function after an average follow-up period of 41 months (range: 12–63 months) [45]. Similarly, Ronga et al. reported satisfactory clinical outcomes in patients who underwent MPFL reconstruction using hamstring tendon autograft (average follow-up: 41 months) [52]. Regarding the association with knee osteoarthritis, Nomura et al. reported that MPFL reconstruction showed no or slight progression of knee osteoarthritis (average follow-up: 11.9 years) [53]. Systematic studies have also been conducted to assess the surgical outcomes of MPFL reconstruction. A systematic review conducted by Smith et al. suggested that MPFL reconstruction might provide favorable clinical and radiographic outcomes [11]. In a recent systematic review of 14 articles, Schneider et al. investigated both subjective and clinical outcomes of isolated MPFL reconstruction [54]. They reported that isolated MPFL reconstruction provided excellent subjective and clinical outcomes, confirmed by the Kujala score, rate of return to sports, and rate of postoperative recurrent instability. Moreover, in children and adolescents with open growth plates, anatomic reconstruction of the MPFL has been reported as a safe and effective surgical procedure [55]. However, MPFL reconstruction has been associated with a considerable complication rate. According to a systematic study by Shaha et al., the overall complication rate associated with MPFL reconstruction was 26.1% (164 out of 629 knees). The complications ranged from minor to major and included patellar fracture, postoperative instability, flexion loss, and pain. Therefore, great caution is needed while planning this surgical procedure. Further high-level studies with uniform reporting of methodology and clinical outcomes including complications are needed [56].

Summary

Over the past two decades, utilization of surgical MPFL reconstruction has increased along with continuous research and development in surgical techniques. Despite the overall favorable surgical outcomes, challenging problems such as a lack of consensus regarding surgical indications, graft selection, graft tensioning, surgical technique, and indications for other surgical procedures have not been discussed adequately. Further high-level studies should be conducted to address these issues.

The cause of patellofemoral instability is multifactorial and there is still no conclusive evidence that a particular surgical option is superior to others. Hence, thorough evaluation of proper patient selection as well as individualized surgical planning is required to yield successful outcomes.

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Basic Principles Including Ideal Targeting Point of High Tibial Osteotomy

Yong In

Abstract

In this chapter, we described various methods for preoperative planning in high tibial osteotomy (HTO) including Dugdale method, Miniaci method, intraoperative adjustments, computer navigation, and patient-specific instruments, and so on. Many patient factors such as medial tightness and lateral laxity not only bony deformity can affect final alignment following HTO. Surgeon should understand various methods targeting ideal alignment during HTO.

Keywords

High tibial osteotomy · Planning · Correction · Alignment · Targeting

The use of high tibial osteotomy (HTO) was first suggested by Jackson as a surgical procedure for treating medial compartment osteoarthritis of the knee [1]. Its effectiveness has been evaluated based on clinical findings, radiologic findings, and scintiscanning. It is fundamental and essential to evaluate preoperative weight-bearing line and make proper preoperative planning for successful operation. In 1979, Fujisawa et al. [2] used the point where the mechanical axis of the limb passed through the level of the tibial articular surface as an index of the degree of deformity. Medial compartment osteoarthritis of knee is generally observed in varus deformity knee. Thus, in most cases, preoperative mechanical axis of the limb passes through the medial side of tibial articular surface (Fig. 1). To obtain successful clinical and radiological results, alteration of the mechanical axis should be made to the proper position (Fig. 1).

In studies that compare arthroscopic findings in the medial compartment before and after the operation, reduction in ulcers is observed in those whose postoperative mechanical axis passes through the lateral compartment of tibial articular surface. In those whose postoperative mechanical axis passes through the lateral compartment of tibia more than 30% from midline, unicondylar weight-bearing is found. Such overcorrection can result in subsequent arthritis of the lateral compartment, MCL laxity, and progressive valgus deformity.

To make the mechanical axis with 3–5 degrees valgus, the mechanical axis should pass through slight lateral to the lateral tibial spine. This point, the so-called Fujisawa point, is from 62% of the tibial plateau width when measured from the edge of the medial tibial plateau. It is widely accepted as a target point of the high tibial osteotomy.

Y. In (✉)
Department of Orthopaedic Surgery, Seoul St. Mary's Hospital, College of Medicine, The Catholic University of Korea, Seoul, Republic of Korea
e-mail: iy1000@catholic.ac.kr

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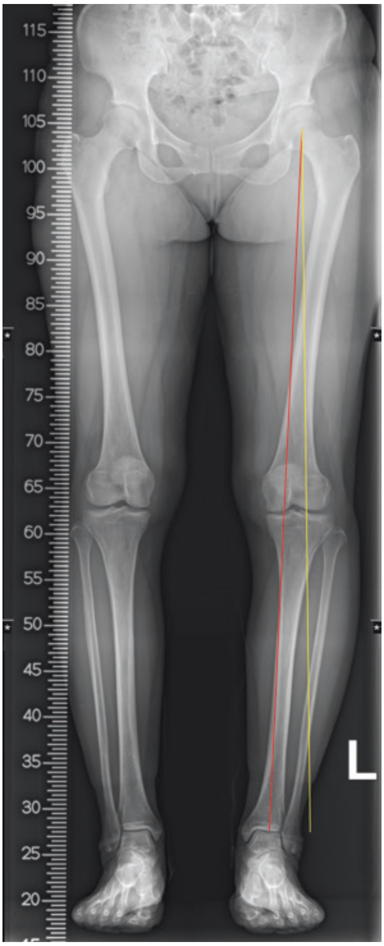

Fig. 1 Preoperative mechanical axis (red line) and corrected mechanical axis (yellow line) passing through the Fujisawa point at tibial plateau level

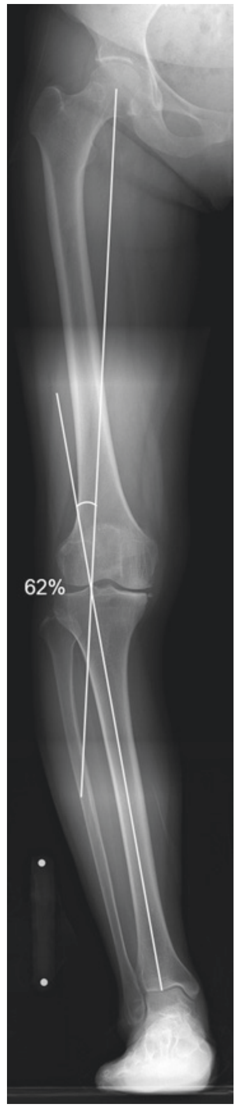

Fig. 2 Graphic depiction of the method used to calculate the correction angle of an HTO using a full-length, non-weight-bearing, anteroposterior roentgenograph of the lower extremity. Lines from centers of the femoral head and tibiotalar joint converge at the 62% coordinate form the desired angle of correction, resulting in a weight-bearing line passing through the coordinate

To obtain satisfactory results in high tibial osteotomy, it is very important to let the mechanical axis pass through the Fujisawa point described above. Therefore, various methods that can be used preoperatively or intra-operatively have been suggested to determine the correcting angle.

The first method is known as the Dugdale method, in which centers of the femoral head and tibiotalar joint are marked on the full-length radiograph and then the selected coordinate of tibial plateau is identified and marked (Fig. 2). The angle formed by the two lines intersecting at the tibial coordinate represents the angular correction required to realign the weight-bearing line through this coordinate. The second method of determining the correction wedge involves cutting the radiograph in an orderly fashion so that it can be repaired with clear tape (Fig. 3). When performing lateral closing wedge osteotomy, the radiograph is cut horizontally through the line of the superior osteotomy cut. A vertical

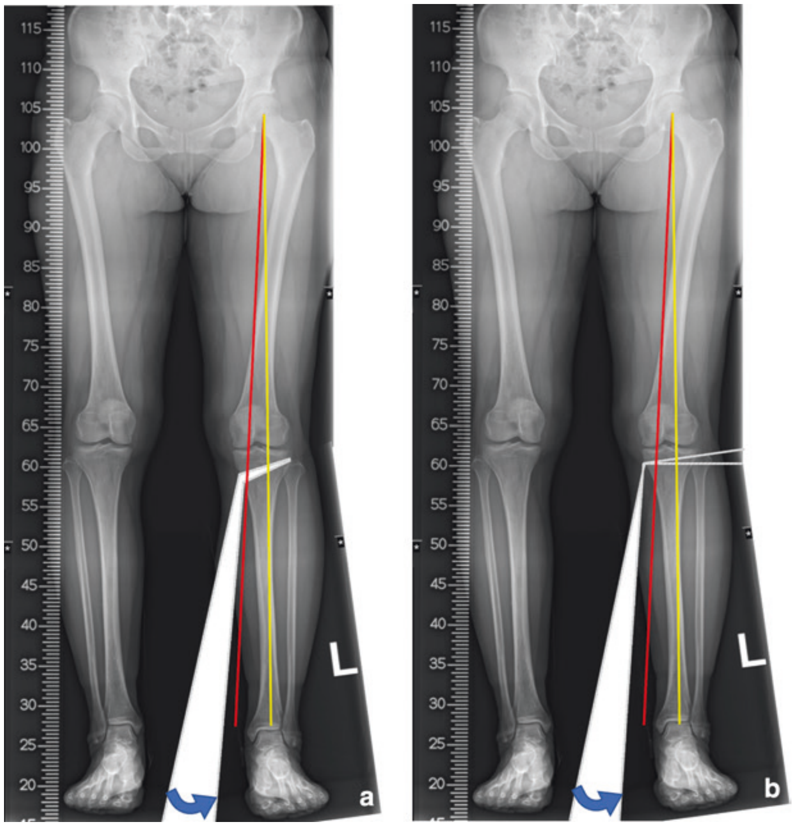

Fig. 3 Graphic depiction of alternate method used to calculate the correction angle of a high tibial osteotomy using a full-length anteroposterior roentgenograph of the lower extremity. The roentgenograph is cut (see text) to allow the center of the femoral head (CFH), the 62% coordinate, and the center of the tibiotalar joint (CTTJ) to become colinear. The angle of the resulting wedge of roentgenograph overlap equals the desired angle of correction. **a** Medial open wedge osteotomy, **b** Lateral close wedge osteotomy

cut is then made to converge with the first cut at the level of the medial cortex, leaving a 2-mm uncut hinge at the medial cortex. The distal portion of the radiograph thus created is then rotated laterally until the center of the femoral head, the coordinate point on the tibial plateau and the center of the tibiotalar joint are all colinear. With the radiograph taped in this position, the angle of the wedge formed by overlap of the two radiograph segments is then measured. If medial open wedge osteotomy is performed, the open angle can be measured after being cut by the lateral cortex level and created into diverge. The measured angle is then compared to the value obtained with the first method. If there is a discrepancy between these two correction wedge values, the procedure is repeated [3].

Another method is known as the Miniaci method (Fig. 4). In this method, a line is drawn from the planned position of the medial corticoperiosteal hinge to the center of the ankle joint. Because recommendations of Fujisawa et al. are now followed, a second line is drawn for the projected mechanical axis that passes from the center of the femoral head through a point 30%–40% of the width of the lateral tibial plateau. It is extrapolated to the level of the projected position of the ankle. A third line is then drawn from the medial corticoperiosteal hinge to the projected position of the center of the ankle. The first and third lines thus subtend an angle which is the desired angle of correction. If medial opening wedge osteotomy is chosen, the hinge is positioned on the medial cortex and measured [4].

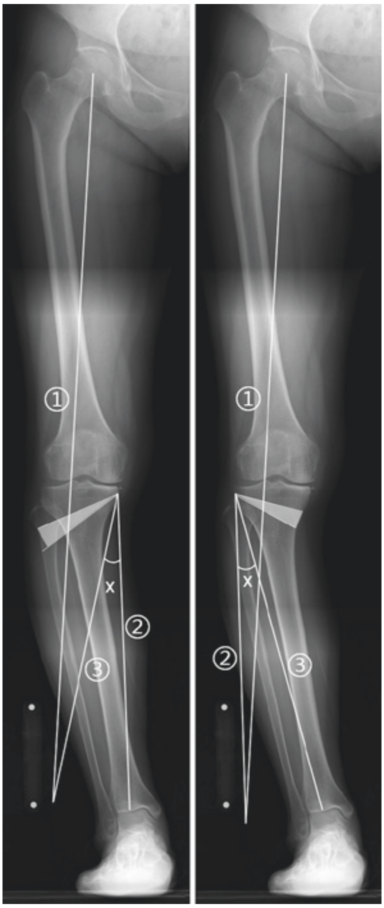

Fig. 4 (Left) Lateral closing wedge osteotomy. Preoperative planning steps to determine the amount of correction necessary to result in a mechanical axis that passes through a point 30%–40% the width of the lateral tibial plateau. Line ① is the predicted mechanical axis. It starts at the center of the femoral head, passing through a portion of the lateral tibial plateau. It is measured to be between 30% and 40% of the lateral plateau width and extrapolated to the level of the projected position of the center of the ankle. Line ② runs from the medial corticoperiosteal hinge or pivot point where arms of the osteotomy will meet, down to the center of the ankle. Line ③ runs from the medial pivot point to the projected position of the center of the ankle. The angle x subtended by lines ② and ③ is the desired amount of correction. (Right) Medial opening wedge osteotomy

Another method uses computer-based modeling to determine the HTO correction angle. A computer-based model simulating HTO in the coronal plane is created using digital radiographic data and theoretical intervention. Digital images are obtained using a standardized protocol with knee and ankles held in a predetermined position. Validated measurement references are provided with images. A series of anatomical landmarks are identified using a MATLAB script to enable a predetermined osteotomy plan to be executed in silico. A simulated HTO is then performed to calculate the opening distance required to deliver the weight-bearing line through the optimal position of the tibial width. Correction to the desired percentage is achieved with an optimization function. A transformation matrix is used to rotate the ankle about the lateral hinge point. The optimum opening distance is then calculated based on this angle and the geometry of the tibia [5].

The whole leg radiograph is an accurate and reproducible exam. It cannot be used intraoperatively. Fluoroscopy of the knee is a method typically used intraoperatively. The center of the femoral head is visualized with fluoroscopy and marked with an adhesive metal clip on the inguinal skin. The center of the ankle also is determined with fluoroscopy and a clamp is placed over it. Now the rod or electrocautery cord could be placed in a straight line between the center of the hip and ankle. During the procedure, the patella is facing upward. It is regularly checked with fluoroscopy. Wedges are inserted under fluoroscopy control until the mechanical axis is projected in the lateral tibial eminence. Since the tibial plateau has no anatomical landmark other than the tibial eminence, the lateral tibial eminence is used as the reference point for the mechanical axis [6].

Intraoperative assessment and adjustment of alignment are inevitably performed with the patient in a supine non-weight bearing position. The discrepancy in alignment between intraoperative assessment and actual standing occurs because the lower limb alignment changes from varus preoperatively to valgus after medial open wedge high tibial osteotomy. After collecting the angle planned, lower limb alignment is evaluated under valgus stress to the knee joint (Fig. 5). Valgus stress is applied to the knee joint manually using the valgus bar until the lateral femoral and tibial condyles contact each other.

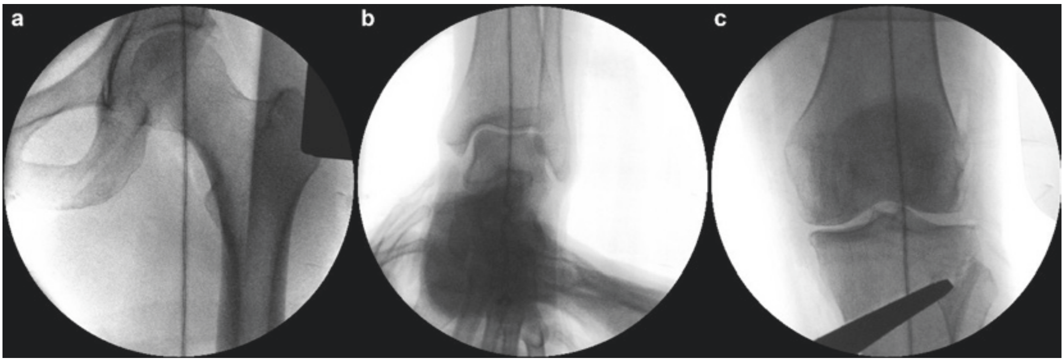

Fig. 5 Intraoperative fluoroscopy

If the electrocautery cable is on the Fujisawa point target line under valgus stress to the knee joint, the correction is accepted without further adjustment. If the cable is not on the Fujisawa point under valgus stress, the angle is adjusted [7] (Fig. 6).

One promising approach is to improve precision by application of navigation system. Computer-assisted intraoperative visualization of limb alignment is performed. At the start of surgery, navigation pins are anchored in the region of the distal femur or proximal tibia using 4.5 mm screws. These pins are positioned at an angle of 90’ to the diaphyseal axis and 30–45’ from the medial side to the vertical axis so that the transmitter when attached is constantly visible to the camera regardless of limb position. Based on this information, an optimal alignment can be obtained [8].

The following is a method using 3D computer-aided design weight-bearing simulated guidance. Deformity of the lower extremity is normally evaluated from alignment in the weight-bearing posture during standing. However, during the CT acquisition process, the patient is in a laying down posture. The obtained alignment of 3D lower extremity from the CT scan is therefore not similar to the standing posture. The alignment of the lower extremity obtained from CT scan is adjusted using the 2D radiographic images taken in the true AP standing posture. Using CAD software, the created 3D models are then cut as medial open-wedge osteotomy to provide anatomical tibiofemoral axis. Preoperative medial opening gap and resected bone are obtained and noted in preoperative planning [9].

Additionally, a study using patient-specific instrument (PSI) guides in high tibial osteotomy has also reported precise creation and distraction of HTO wedge. That study integrated 2D and 3D preoperative planning to create a PSI guide that could most likely render outcomes close to the planning. A surgical guide was designed to fit the medial tibial surface with four pinholes to stably fix the guide on the targeting region of the patient’s bone. A cutting slot and a guiding plane were provided for biplanar osteotomy. The edge of the cutting slot was parallel to the lateral hinge and the sawing depth was defined as a specific integer from the slot edge to hinge. The guiding plane coincided with the anterior cutting plane. Thus, the oscillating saw could lean against the plane while sawing. For intraoperative confirmation of the correction angle, two extended arms with two holes above and below the osteotomized wedge were respectively created. These two holes were designed not to be initially aligned until the wedge was distracted to the correction angle as described in preoperative planning. At this moment, an aligning rod was used to pass through the two aligned holes to assist the surgeon in determining whether the correction angle was achieved. PSI guide has advantages in that it can save time and decrease radiation. In addition, it is relatively easy to use [10].

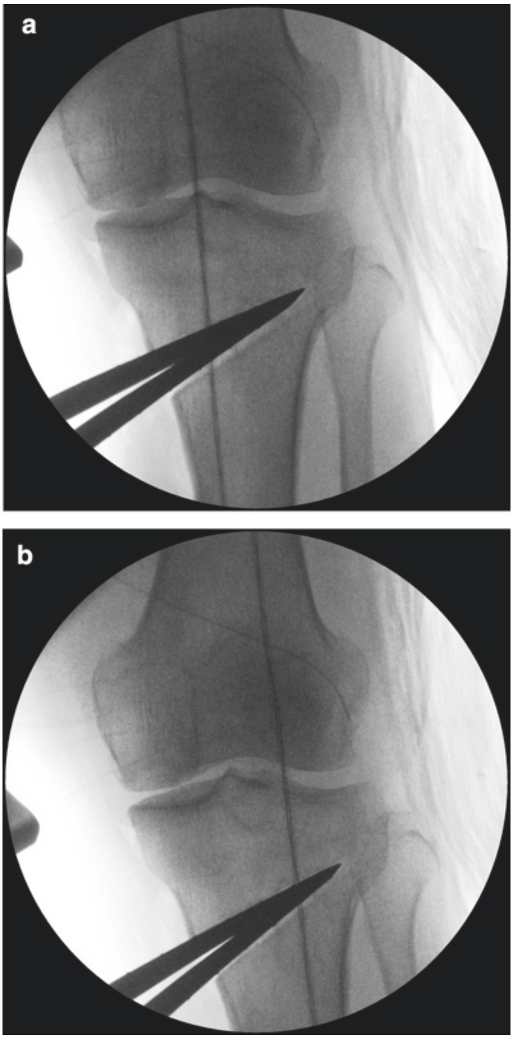

Fig. 6 A valgus bar is attached to the lateral knee joint space preoperatively. **a** Before valgus stress is given, the mechanical axis passes through medial tibial spine. **b** Under valgus stress, the mechanical axis passes through the Fujisawa point

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Surgical Treatment and Overcoming Complications of High Tibial Osteotomy

Jae Doo Yoo, Jeong Soo Park, Jae Yoon Chung and Min Gyue Park

Abstract

High tibial osteotomy (HTO) is a well-established technique for the treatment of medial osteoarthritis of the knee with varus malalignment. OWHTO has several advantages over CWHTO. However, several pitfalls should be avoided such as lateral hinge fracture, increased tibial slope angle, joint line obliquity, popliteal artery injury, delayed or nonunion. The surgical details of OWHTO surgical technique are described in this chapter.

Keywords

Proximal tibia · Open wedge · Osteotomy · Osteoarthritis · Knee · Technique

High tibial osteotomy (HTO) is a well-established technique for the treatment of medial osteoarthritis of the knee with varus malalignment. Generally, two basic techniques are performed, a lateral closed-wedge HTO (CWHTO) and a medial open-wedge HTO (OWHTO).

CWHTO is the historic approach and is more familiar to some surgeons. But OWHTO has several advantages over CWHTO, including easier control of the degree of correction, less extensive soft tissue dissection, ability to correct the alignment in two planes (coronal and sagittal), no need for fibular osteotomy, little risk of peroneal nerve injury, no limb shortening, no bone loss, easier conversion to arthroplasty. Because of these advantages over CWHTO, the OWHTO has gradually taken the place of the CWHTO [1]. Previous studies have concentrated on comparing the two techniques with regard to correction angle, posterior tibial slope, patella height, and complications. However, these comparative studies have no consistently demonstrated either technique to be superior to the other. The author usually performs OWHTO technique and tries to describe OWHTO as the surgical technique.

Surgical Technique of Open-Wedge HTO

Preoperative Planning

One of the most important factors in determining the success of the HTO is making an accurate preoperative planning.

The author has been using the Miniaci method, (Fig. 1) which estimates objective calibration of mechanical axis by using preoperative AP long leg weight radiography.

J. D. Yoo (✉) · J. S. Park · J. Y. Chung · M. G. Park
Department of Orthopaedic Surgery, Ewha Womans University School of Medicine, Seoul, Republic of Korea
e-mail: koreanknee@gmail.com

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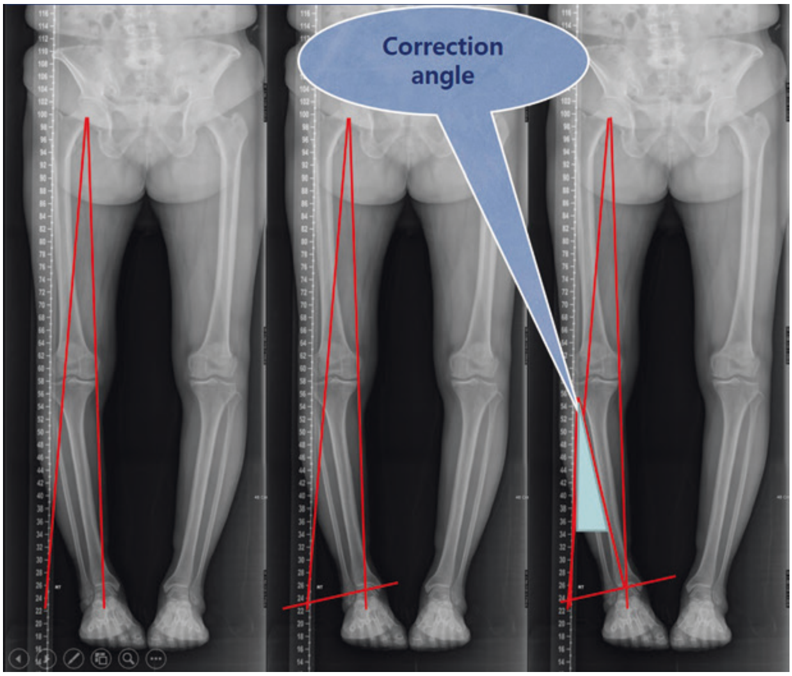

Fig. 1 The Miniachi's method

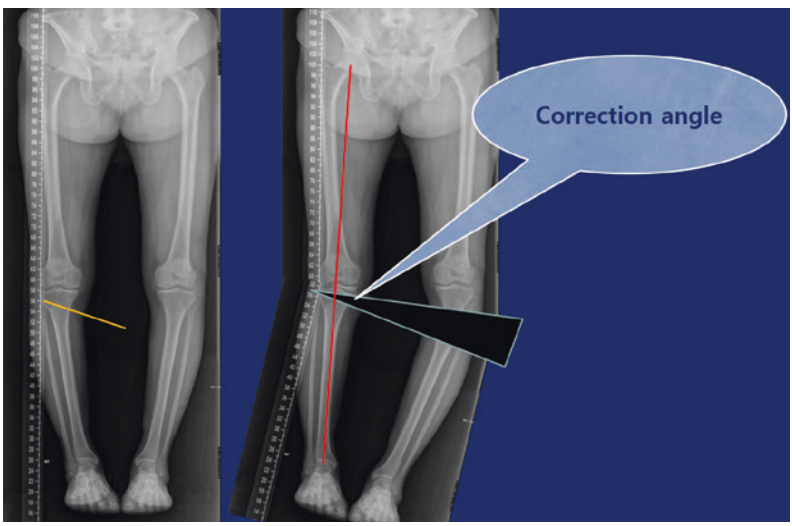

Fig. 2 The real-size scanogram. Scannography measurement method. A template was cut through the osteotomy site and the tibia was rotated until the weight-bearing line passed through the 62% coordinate

If medial joint space narrowing is noted, mechanical axis is corrected to the 62% point of the tibial plateau as Fujisawa suggested. On the other hand, if the medial compartment is not narrow and the joint space is relatively preserved, the plan is established by which the mechanical axis crosses between the center of the knee joint and the Fujisawa point.

Another method is to print out the scanogram in real size and actually check the change of mechanical axis according to the osteotomy gap (Fig. 2).

Although real-size scannogram has an advantage in that the accurate osteotomy gap can be measured prior to surgery, it is difficult to use in an institution that does not support real-size scanogram printing.

Diagnostic Arthroscopy

Diagnostic arthroscopic procedure is used in all cases, checking the state of the cartilage of the medial and lateral compartment, assuring if there are any intra-articular lesions.

The author proceeds operation regardless of any chondromalacia of the femoral trochlea or the patella that is found during the procedure (Fig. 3).

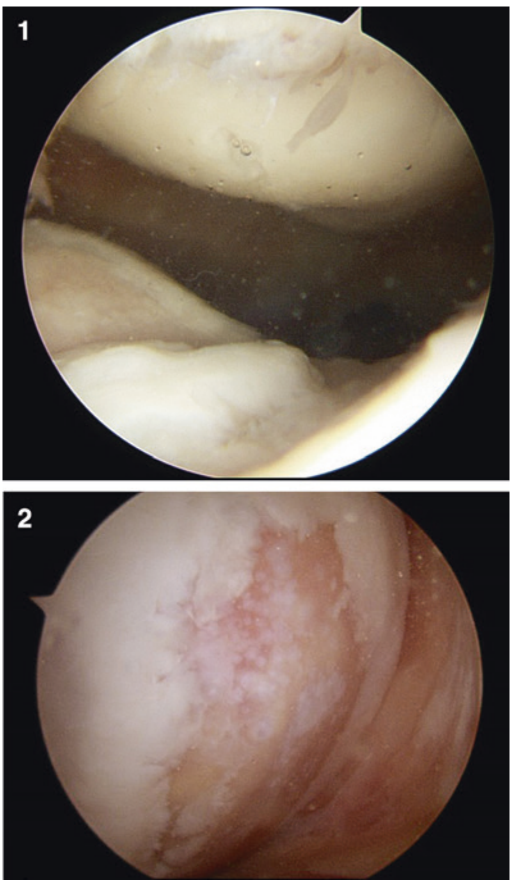

Fig. 3 Diagnostic arthroscopic procedure. 1. Femoral trochlear groove chondromalacia. 2. Medial femoral condyle cartilage defect

Skin Incision

The anatomical markers are drawn on the skin with the knee flexion at 90 degree. Generally, the 5 cm longitudinal incision is done at the middle point between medial border of the patellar tendon and the tibial posterior border. Another 6–8 cm oblique incision can be done from 5 cm inferior to the articular surface and just anterior aspect of the pes anserinus attachment site to posteromedial aspect of tibial plateau. However, the author usually has used longitudinal skin incision near the medial border of the patellar tendon because it is easy to extend the incision when patients are converged to total knee replacement arthroplasty (Fig. 4).

Medial Collateral Ligament (MCL) Release

Partial dissection of pes anserinus tendon as reverse L-shape is done, and then the presence of the superficial MCL is checked, followed by releasing MCL from the posteromedial aspect of the tibia using cobbs elevator. The author usually releases the MCL from the tibial attachment site rather than cutting it out (Fig. 5). Expose the medial tibial attachment of patella tendon with protecting neurovascular structures using Hohmann retractor posteriorly.

Guide Pin Insertion

Decision of the osteotomy site is performed by viewing the true anteroposterior and lateral knee joint image using C-arm fluoroscopy with the full extension of the knee joint. And then two 2.5 mm k-wires are inserted parallel to the

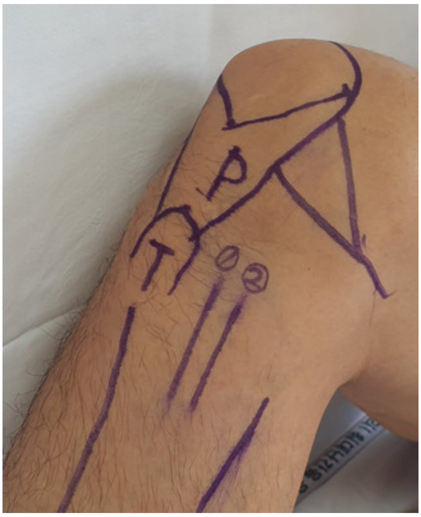

Fig. 4 Skin incision, P: patella tendon T:Tibial tuberosity. ①: Author's skin incision ② Standard longitudinal skin incision

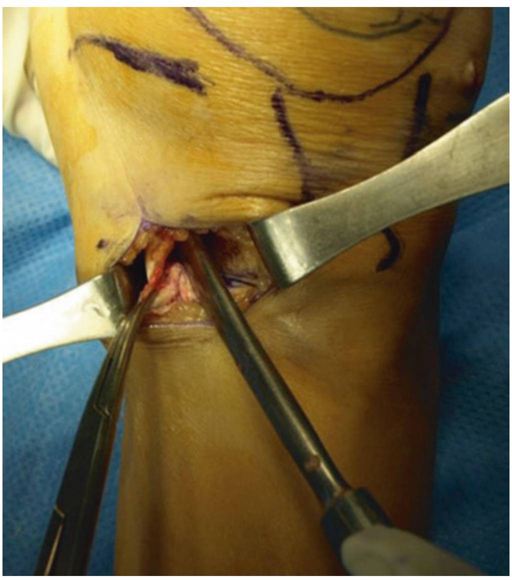

Fig. 5 MCL release from the tibial attachment site

proximal tibial posterior slope. Begin above the pes anserinus tendon attachment site at least 3 cm away from the medial tibial articular surface, and insert k-wires to the point 1.5 cm or more below the lateral tibial articular surface at the level of fibular head (Fig. 6).

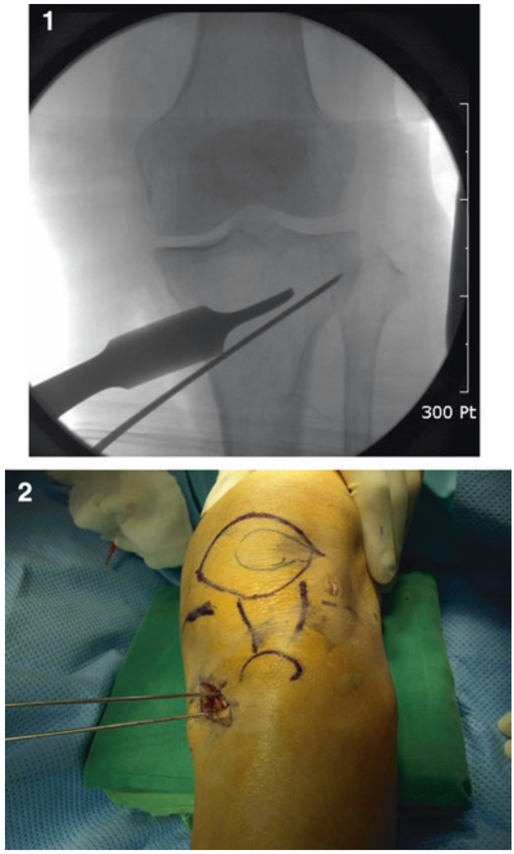

Fig. 6 Guide pin insertion. 1. Starting point: above the pes anserinus tendon attachment site at least 3 cm away from the medial tibial articular surface. End point: 1.5 cm or more below the lateral tibial articular surface at the level of fibular head. 2. Two 2.5 mm k-wires are inserted

Biplane Osteotomy

In order to calculate the depth of the saw that is about to be inserted into the osteotomy, the length of the inserted part of the guide pin is measured and marked it on the saw. Since about 1 cm of the lateral tibial cortical bone acts as a hinge when opening the osteotomy, the length with smaller than 1 cm of the inserted pin is marked at the saw.

When the osteotomy is performed, the knee should be flexed at 90 degrees and the protective device such as Hohmann retractor should be applied to the tibial posterior side to prevent

Fig. 7 Tibial tuberosity osteotomy in frontal plane

neurovascular structure damage. Before the osteotomy, the author usually makes a slot on the site of osteotomy using a micro saw that shakes less. The author usually performs tibial tuberosity osteotomy of the frontal plane first. With the vertical saw inserted into the back of the patellar tendon and then osteotomy is continued along the slot previously made with a micro saw (Fig. 7). The osteotomy for wedge is then performed along with below the inserted k-wires using an oscillating saw. The first and second osteotomy planes should maintain an angle of about 110 degrees. Any insufficient osteotomy should be completely osteotomized with the osteotome. In particular, the posterior cortical bone should be checked if it is completely osteotomized. This L-shaped biplanar osteotomy has the advantage of improving rotational stability and anterior stability of the osteotomy surface when knee is extended.

Gap Opening

The osteotomized surface is opened using three to four chisels. The opening of the osteotomized surface should be done slowly with great care to prevent lateral cortical hinge fracture and secondary intra-articular fracture (Fig. 8). Then, using a laminar spreader, the osteotomy surface is opened by the length or angle planned before

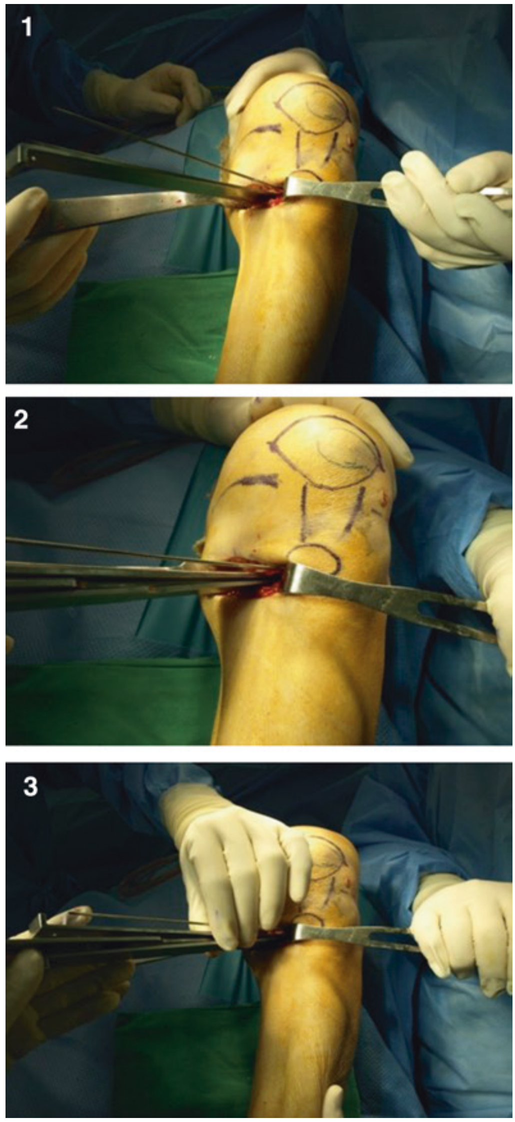

Fig. 8 Opening of osteotomy gap with chisels. The opening of the osteotomized surface should be done slowly with great care. 1. One chisel is inserted. 2. Second chisel is inserted. 3. Third chisel is inserted

surgery (Fig. 9). And check if there is enough gap or distance as far as wanted using a ruler (Fig. 10). At this time, make a trapezoidal gap to prevent the increase of the posterior tibial slope and for this, make the anterior gap to be about 50–60% of the posterior gap (Fig. 11).

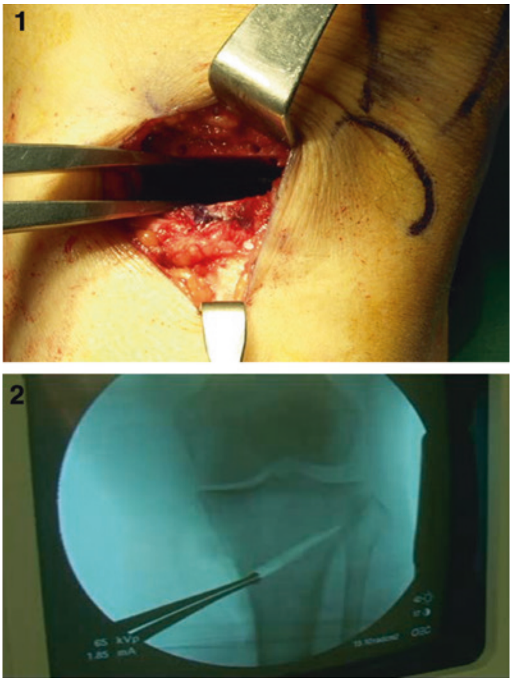

Fig. 9 Using a laminar spreader, the osteotomy surface is opened. 1. Opening of the osteotomy gap with laminar spreader. 2. Fluoroscopic image of the osteotomy gap

Fig. 10 Checking the gap size with ruler

Check the Mechanical Axis

Once the gap has been opened as intended, recheck mechanical axis that crosses hip–knee–ankle line using the C-arm and alignment rod intraoperatively. At this moment, axial compression force is should be applied to give weight-bearing effect.

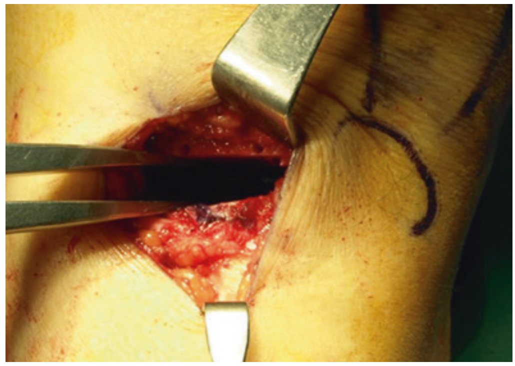

Fig. 11 Trapezoidal gap. Anterior gap is to be about 50–60% of the posterior gap

Plate Fixation

A plate is inserted through the subcutaneous tunnel, parallel to the tibial shaft at the center of the anteromedial tibial surface. Insert the two spacer bolts to the plate in advance to make a space between the plate and the bone. And then insert the three locking screws in the most proximal hole of the plate. And then temporarily insert the lag screw just distal to the osteotomy site. This lag screw pulls the distal bone fragment toward the plate resulting in lateral cortical hinge area to be compressed by plate elasticity. It needs to be careful not to overtighten the lag screw in order to bring the plate into close contact with the cortical bone; otherwise, fracture can occur at the hinge site (Fig. 12). Fix the remaining distal bone fragment with the locking screws and lastly replace the temporarily inserted lag screw with the locking screw.

Bone Graft

Effective osteosynthesis after osteotomy affects clinical outcome and knee joint range of motion, therefore, it is known as one of the most important factors of healing outcome. Bone grafts are often performed for osteosynthesis in this context.

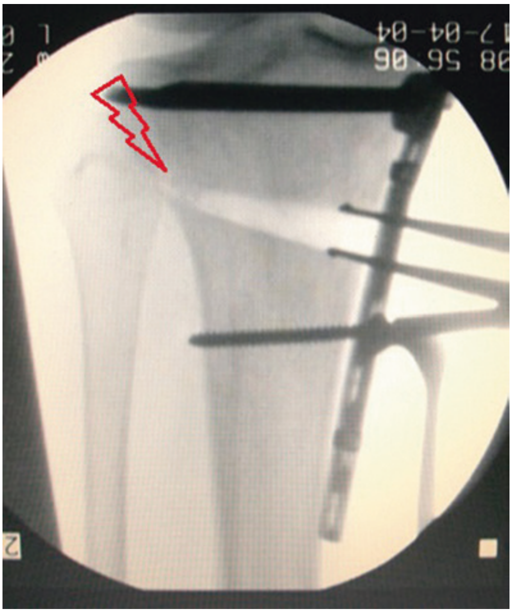

Fig. 12 Plate fixation. Lag screw pulls the distal bone fragment toward the plate resulting in lateral cortical hinge area to be compressed by plate elasticity. If the lag screw is overtightened, fracture can occur at the hinge site

The author performs allogenic bone graft when more than a 10 mm correction gap is required.

Closure

Since there is always a risk of vascular damage, it is important to decompress the tourniquet and check for bleeding carefully before wound closure. If suction drainage is inserted, place it as far as possible from the osteotomy site.

Rehabilitation

From the day after surgery, partial weight-bearing ambulation with crutches is allowed. With the removal of suction drainage, continuous passive motion (CPM), periarticular muscle strengthening exercise, flexion, and extension exercises are performed immediately. From 6 weeks after the operation, if the radiological bone union is seen, full weight-bearing ambulation is allowed.

Complications

Lateral Hinge Fracture

As one of the most common complications in the OWHTO, lateral hinge fracture usually occurs when elastic preload is applied to the lateral hinge during wedge distraction after osteotomy or when osteotomy is performed. According to the literature, the incidence rate is about 20–30% and it is affected by the amount of correction, insufficient osteotomy, kind of plate, hinge position, and osteotomy level.

Lateral hinge fractures can cause the loss of correction, implant failure, malunion and nonunion. Kurenmsky et al. [2] reported that at least 4 degrees of correction loss can be induced when lateral hinge fracture occurred. Takeuchi has been classified lateral hinge fractures into three types (Fig. 12); type I comprises fractures that involve an extension of the osteotomy line and are just proximal to or within the tibiofibular joint, type II is the fracture reaching the distal portion of the proximal tibiofibular joint, type III comprises lateral plateau fracture [3]. Among them, type II is known to be related to delayed union and nonunion.

Several methods have been introduced to reduce the occurrence of lateral hinge fractures. The guide pins should be inserted 1 cm away from the lateral cortex, starting at the upper margin of the pes anserinus tendon. It is good to use a chisel to open slowly and gradually when opening the osteotomy gap.

Han et al. [4] defined the area between the fibular tip and the circumference line of fibular head to 'safe zone,' and to reduce the occurrence of the lateral hinge fractures, they emphasized that osteotomy plane should be toward this safe zone. Ogawa et al. [5] reported that sufficient osteotomy should be done so that both anterior and posterior cortex osteotomy site of the tibia should be located to the lateral side of the fibular medial edge on axial plane. That is, they emphasized making enough osteotomy from anterolateral to posterolateral aspect. However, because excessive osteotomy may result in lateral hinge fractures when gap opening is done, the lateral cortex should be remained at least about 1 cm. In the case of the plate, Because long locking plate provides better stability when lateral hinge fracture occurs, it is better to use a long locking plate such as Tomofix plate (Synthes, Bettlach, Switzerland) when performing OWHTO.

Turmen et al. [6] reported that when large correction angle is needed, biplanar osteotomy can be used to reduce the risk of lateral hinge fracture than monoplanar osteotomy. Most lateral hinge fractures occur intraoperatively, but some of these cannot be detected on postoperative plain radiographs. CT scans would enable the detection of lateral hinge fractures that would otherwise have been mistaken (Figs. 13 and 14) [7].

Increased Posterior Tibial Slope Angle (PTSA)

OWHTO has been associated with an unintentional increase in the posterior tibial slope angle (PTSA). The increased PTSA causes overloading of anterior cruciate ligament and anterior translation of tibia, resulting in degradation of articular cartilage and degenerative osteoarthritis. [8] Therefore, efforts are needed to prevent the increase of PTSA during open wedge HTO, and several methods have been introduced.

First, wedge gap should be of trapezoidal shape, in which the anterior gap is smaller than the posterior gap. Song et al. [9] said that the opening gap ratio (anterior opening gap/posterior opening gap) should be 67% to maintain preoperative PTSA after OWHTO. Likewise, Noyes et al. [10] reported it as 50%. The author aims 50–60% of opening gap ratio.

Moreover, there should be enough posterior soft tissue release, making complete posterior cortex cut, making bone spreader and plate be applied to posterior aspect of the gap.

The hinge position also associated with the increase of PTSA, Jo et al. [11] reported that when the hinge was applied to lower than the standard hinge point, an increase in PTSA occurred, so he said that the hinge point should not be a low position.

Ogawa et al. [12] said that when wedge-shaped spacer (hydroxyapatite, β-tricalcium phosphate, autologous or allogenic bone) is used, PTSA can be increased when wedge spacer is inserted more anterior to posterior direction. On the contrary, PTSA can be decreased when it is inserted more posterior to anterior direction.

Meanwhile, PTSA can be adjusted by the preoperative states of the patient. In patients

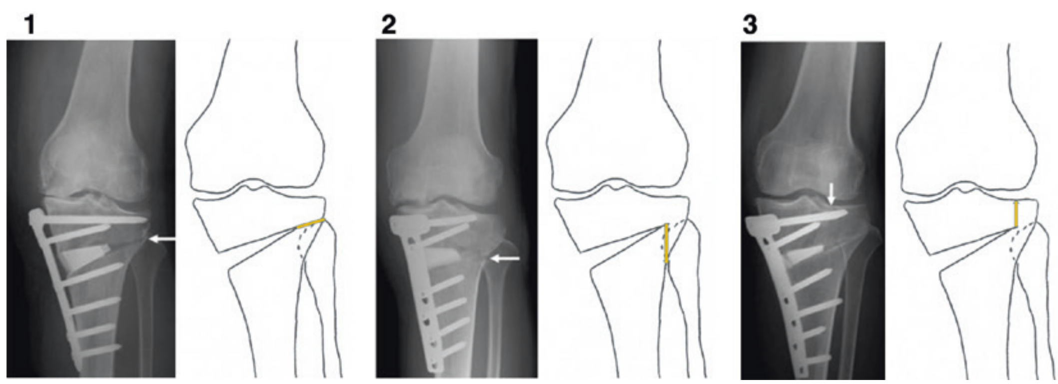

Fig. 13 1. Takeuchi's type 1 fracture. Fractures line: just proximal to or within the tibiofibular joint. 2. Takeuchi's type 2 fracture. Fracture line: distal portion of the proximal tibiofibular joint. 3. Takeuchi's type 3 fracture. Intra-articular lateral plateau fracture

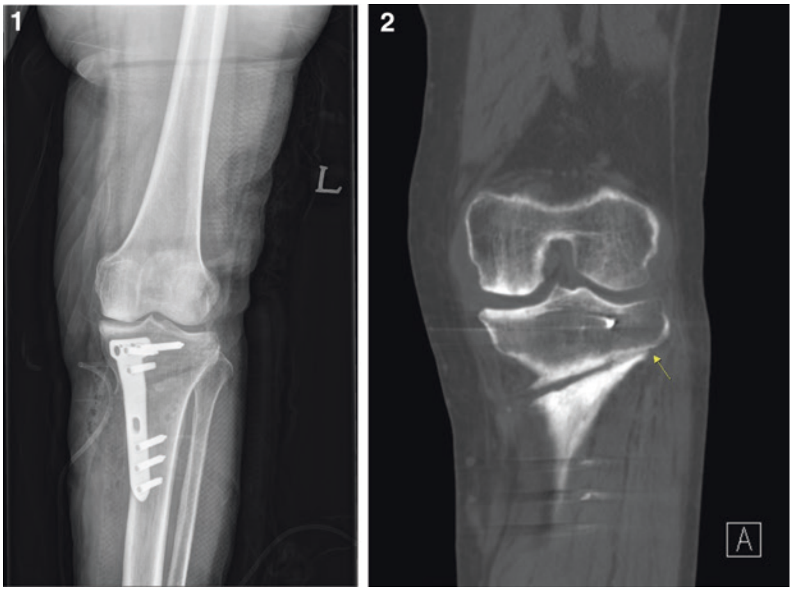

Fig. 14 Diagnosis of lateral hinge fractures. 1. Lateral hinge fracture is not visible in simple AP radiograph. 2. CT scan can detect the lateral hinge fracture that was not visible in simple radiograph

who were not able to fully extend the knee before the surgery, a decrease in PTSA might be helpful for improving knee extension. Moreover, it also might be helpful for patients who had anterior cruciate ligament injuries by reducing the anterior displacement of the tibia. However, increased PTSA may help in patients with posterior instability or hyperextension of the knee joint. As Ogawa et al. insisted, it is expected to expand the surgical indications of osteoarthritis patients with cruciate insufficiency by adjusting PTSA by changing the inserting direction of the wedge spacer.

Correction Error (Overcorrection, Under Correction)

In the case of excessive correction during the operation by error, excessive load on the normal lateral compartment can occur, resulting in degenerative arthritis. Likewise, in the case of under correction, the planned transfer of mechanical axis might not be done properly and symptoms of patients can not improve, leading to surgical failure [13, 14].

The preoperative alignment assessment is usually done through weight-bearing radiography, but the intraoperative alignment assessment is done under the non-weight-bearing condition, which causes a discrepancy between preoperative alignment assessment and postoperative alignment. Moreover, this discrepancy can be increased by severe soft tissue laxity (varus or valgus laxity) due to the effects of weight-bearing conditions on alignment changes in lax knees [15].

In order to compensate for this discrepancy, Sim et al. [16] insisted that the lower extremities should be placed in neutral and exerted the force axially from the soles of the feet for the alignment assessment. And Kim et al. [17] said that alignment assessment should be done under valgus stress. The author mainly uses the former method.

On the other hand, soft tissue laxity itself causes alignment correction errors, because not only bony correction but also soft tissue correction occurs at the same time after HTO. Because surgeons usually calculate bony correction only in preoperative alignment assessment, overcorrection might happen as much as soft tissue correction occurs.

Joint line convergence angle (JLCA) is the angle between articular surface of distal femur and proximal tibia in the anteroposterior radiographs of standing patients. The normal range is 0–2 degrees and is measured to assess soft tissue laxity. Recently, Lee et al. [18] said that the overcorrection after HTO in a knee with soft tissue laxity is due to a reduction of JLCA after soft tissue correction. And Ogawa et al. [19] also reported similar results. Therefore, in the lax knee patients with abnormal JLCA, it is necessary to evaluate preoperative correction angle assessment in consideration of the JLCA reduction that occurs after HTO. There is no consensus on how much angle adjustment is necessary when there is soft tissue laxity. Recently, Ogawa et al. [19] reported that 0.59 degrees of soft tissue correction occurred per 1 degree of JLCA measured under varus stress before the operation. So, they recommended that this should be reflected when calculating the correction angle in patients with abnormal JLCA.

Joint Line Obliquity

In cases of severe varus knee due to proximal tibial varus deformity or combined varus deformity of both the distal femur and proximal tibia, the proximal tibia should be overcorrected to solve these problems by OWHTO, which can increase knee joint line obliquity in the coronal plane [20–23]. This joint line obliquity causes increased joint shearing stress and femoral subluxation, resulting in poor clinical outcomes.

Double-level osteotomy is considered a good alternative in patients with severe varus malalignment. Schroter et al. [24] reported that double-level osteotomy in severe varus malalignment patients can prevent joint-line obliquity with good clinical outcomes.

Even though there is no consensus on what degree of joint line obliquity is appropriate, Conventry et al. [25] said that angles less than 10 degrees of joint line obliquity are acceptable. Babies et al. [21] reported that knees with a postoperative joint line inclination of 4 degrees or less could achieve a high survival rate.

The important radiologic parameter to evaluate joint line obliquity is medial proximal tibial angle (MPTA) and the normal person has an average of 87 degrees MPTA [26].

Nakayama et al. [27] said that the shearing stress increases when the joint line obliquity is 5–10 degrees, consistent with the 95 degrees of MPTA. Therefore, he said that if the preoperative MPTA is expected to be greater than 95 degrees, double-level osteotomy should be performed.

Meanwhile, joint line obliquity can occur when OWHTO is performed on the varus knee with normal MPTA. Therefore, when performing preoperative alignment assessment, MPTA should be measured to determine the origin of varus deformity. After confirming the origin of deformity, deformity correction surgery should be performed.

Popliteal Arterial Injury

Popliteal arterial rupture during HTO is very rarely enough to be reported in a case report but is the most catastrophic complication if it once occurs. It has been reported mainly in CWHTO and rarely occurs in OWHTO. However, since OWHTO has become popular recently, the occurrence of complications is thought to be underreported. The general recommendation to avoid popliteal arterial injury during HTO is 90 degrees of knee flexion when sawing. But flexion of the knee with 90 degrees does not completely prevent arterial rupture. Shetty et al. [28] used duplex ultrasonography 100 knees to compare the distance of the popliteal artery to the posterior tibial cortex in full extension and 90 degrees flexion. He found that in most cases the distance increased in flexion. But remaining cases showed an opposite behavior where the popliteal artery moved towards the posterior tibial cortex in 90 degrees of flexion. Therefore, even if the knee is flexed at 90 degrees, the sawing should be done carefully. Kim et al. [29] reported in cadaveric studies that the popliteal artery moved away from the posterior tibia as the knee was flexed from 0 to

90 degrees, making strengthened the evidence that the knee should be flexed 90 degrees during sawing. However, he also said that popliteal arterial rupture was not completely prevented with 90 degrees of knee flexion only. Besides this method to reduce the risk of popliteal arterial injury, he emphasized that the sawing angle should be within 30 degrees in the coronal plane when sawing and a protective device should be applied to anterior aspect of the popliteus muscle.

On the other hand, aberrant high branching of the anterior tibial artery is reported in 2–8%, and this artery travels to the ventral side of the popliteus muscle and can be damaged during sawing.

Preoperative MRI may be helpful but since it is not usually taken for HTO, a careful subperiosteal exposure of posterior tibial cortex is needed to reduce the injury. As Kim et al. emphasized, the protective device should be inserted anterior to the popliteus muscles when sawing.

Infection

Infection is a very rare complication after HTO, but if once occurs, it can cause serious adverse effects on clinical or radiological outcomes and may require several additional revision surgeries.

Although there are few studies on the rate of infection after HTO, the frequency of superficial infections is reported as 1–9%, and the that of deep infections is reported as 0.5–4.7% [30].

Smith et al. [31] reported that there is no significant difference in postoperative infection between open-wedge and closed-wedge HTO. And Reichl et al. [32] reported that oblique skin incision was the only significant risk factor identified in the study of the cause of infection after HTO. Lymphedema is a well-known risk factor of skin infection and it has been reported that lymphedema develops well in oblique skin incision. The author has been using a straight anteromedial skin incision.

Delayed Union or Nonunion

Rate of delayed unions after HTO has been reported at 6.6–15%, and that of nonunion has been reported at 1.6–7.0%. And they are more common in OWHTOs than CWHTOs. In OWHTO, osteotomy gap is formed after wedge opening, and it is reported that the frequency of delayed union or nonunion increases when this osteotomy gap is large. Therefore, many literatures agree that bone graft is necessary when osteotomy gap is large. However, there is no uniform criterion for opening gap size that requires bone graft. Slevin et al. [33] said that bone grafts are needed when the osteotomy gap is more than 10 mm. Lobebhoffer et al. [34] and Goshima et al. [35] reported bone graft is needed with more than 13 mm of osteotomy gap. El-Assal et al. [36] and Kolb et al. [37] said it was more than 14 mm. The author performs bone graft when the opening gap is more than 10 mm.

Lateral hinge fractures are also a risk factor for delayed union and nonunion, and Schroter et al. [24] and Goshima et al. [35] said that Takeuchi's classification type 2 is particularly considered to be risky. To prevent lateral hinge fracture, refer to the method mentioned above.

Meanwhile, there are other considerations for reducing delayed union or nonunion. Osteotomy should be performed above of tibial tuberosity because the contact area of cancellous bone becomes smaller when osteotomy is done below the tibial tuberosity, which may prevent bone healing and result in delayed union or nonunion. However, if the osteotomy site is too close to the joint, bone healing may be inhibited due to thin proximal fragments, thus osteotomy should not be done too close to the joint.

Compartment Syndrome

The incidence of compartment syndrome after osteotomy is rare, but it can be serious if it is overlooked, thus, careful observation is necessary after the operation. Because hematoma formation induced by excessive bleeding is the main cause of compartment syndrome, it is important to place the suction drainage at the surgical site so that blood does not accumulate. If compartment syndrome develops, immediate fasciotomy should be performed with hematoma evacuation.

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Minimum Correction of High Tibial Osteotomy with Medial Meniscus Centralization

Hideyuki Koga and Hiroki Katagiri

Abstract

High tibial osteotomy (HTO) is an effective treatment for the medial unicompartmental knee osteoarthritis, and favorable outcomes after isolated HTO have been reported. On the other hand, as long-term results are still not satisfactory, further development of surgical procedures is necessary in order to improve clinical results and survival rates. As a novel surgical procedure for meniscus extrusion, arthroscopic centralization has been developed, and its good clinical outcomes have been reported. In this chapter, a combination of minimum correction open-wedge HTO aiming for neutral alignment and arthroscopic centralization of medial meniscus has been introduced, and a detailed surgical procedure is described. Clinical results at 1-year follow-up were comparable to those after HTO with previously reported combined procedures, with a significant decrease in the joint-line convergence angle. This procedure could expect better long-term clinical and radiographic outcomes as well as a decrease of possible adverse effects by valgus alignment.

H. Koga (✉) · H. Katagiri
Department of Joint Surgery and Sports Medicine, Tokyo Medical and Dental University, Tokyo, Japan
e-mail: koga.orj@tmd.ac.jp

Keywords

Knee osteoarthritis · Meniscus extrusion · High tibial osteotomy · Arthroscopic centralization

Introduction

High tibial osteotomy (HTO) for the medial unicompartmental knee osteoarthritis (OA) is an effective treatment. With a recent development of a locking plate and surgical technique, indication of open-wedge HTO (OWHTO) has been expanded, and favorable outcomes have been reported [1]. On the other hand, long-term results are still not satisfactory, as national registry-based studies have reported that the conversion rate of HTO to knee arthroplasty is approximately 10% at 5 years and approximately 30% at 10 years, respectively, suggesting that further development of surgical procedures is necessary in order to improve clinical results as well as to decrease the conversion rate.

In terms of alignment correction in HTO, it has been recommended that the weight bearing line ratio should be aimed at 62% to obtain good results [2]. Although it has been reported that OWHTO with standard correction does not cause structural changes on the lateral compartment [3, 4], it does accelerate lateral

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compartment OA in cases with discoid meniscus [5] or any other lateral compartment pathologies [6]. In addition, valgus alignment after HTO would cause cosmetic problems or diminish sports performance level, especially in young active patients. In addition, in cases with severe varus alignment, large correction is necessary if the correction target is set at 62% in the weight bearing line ratio, resulting in joint-line obliquity which induces excessive shear stress on articular cartilage [7], lower patient-reported outcomes [8], delayed bone healing [9], and degeneration of patellofemoral cartilage [10].

Meniscus extrusion suggests the loss of meniscal function, diminishing the effective load-bearing mechanism, and degeneration of articular cartilage would thus be accelerated. Extrusion of the medial meniscus (MM) has been reported to be an independent risk factor for development of OA [11, 12] and knee pain in patients with OA [13]. MM extrusion could be caused by posterior root tears or radial tears [14], and after partial meniscectomy [15]. In addition, a recent study reported that medial tibial osteophyte was observed in patients with early-stage OA, and the osteophyte was closely associated with MM extrusion [16]. However, there have been no effective surgical interventions for meniscus extrusion, especially in cases with difficulty in anatomic meniscal repair. Therefore, we have developed a novel procedure called arthroscopic centralization, in which the midbody of the meniscus is centralized onto the rim of the tibial plateau to restore and maintain the meniscus function by repairing/preventing extrusion of the meniscus [17]. Good clinical and radiographic outcomes of this procedure for lateral meniscus extrusion have been reported [18], and indications of the technique have been expanded to lateral compartment OA [19, 20] as well as augmentation of the MM posterior root tear (MMPRT) repair [21]. An animal study also showed that centralization of extruded MM delays cartilage degeneration in a rat OA model [22].

Based on the above considerations, our current procedure for medial unicompartmental knee OA associated with MM extrusion is a combination of minimum correction OWHTO aiming for neutral alignment and arthroscopic centralization of MM, expecting better long-term clinical and radiographic outcomes as well as a decrease of possible adverse effects by valgus alignment. In this chapter, detailed surgical techniques of OWHTO combined with MM centralization and its preliminary clinical outcomes are described.

Surgical Procedure

Indications

Indications of OWHTO combined with MM centralization are cases indicated for OWHTO; namely, relatively active patients with symptomatic medial unicompartmental varus OA after sufficient conservative treatment, and those in which extrusion of the MM is confirmed pre-operatively by coronal view of magnetic resonance imaging (MRI). This procedure and concept are also applicable to cases with MM tears that cause extrusion, such as MMPRT, radial tear, and degenerative horizontal tear, accompanied by varus alignment (weight bearing line ratio less than 40%). In such cases, meniscus repair alone would result in failure; combined HTO and augmentation of the repair by arthroscopic centralization is recommended. Our strategy for varus OA indicated for OWHTO is shown in Fig. 1.

Preoperative Planning

An anteroposterior (AP) long-leg weight-bearing radiograph is used for preoperative planning. The weight bearing line ratio is aimed at 57%. We would like the alignment to be as neutral as possible (ideally 50%), but we would also like it not to be undercorrected. Considering the possible error, we set the weight bearing line ratio at 57%. Other parameters such as mechanical medial proximal tibial angle (mMPTA), mechanical lateral distal femoral angle (mLDFA), and joint-line convergence

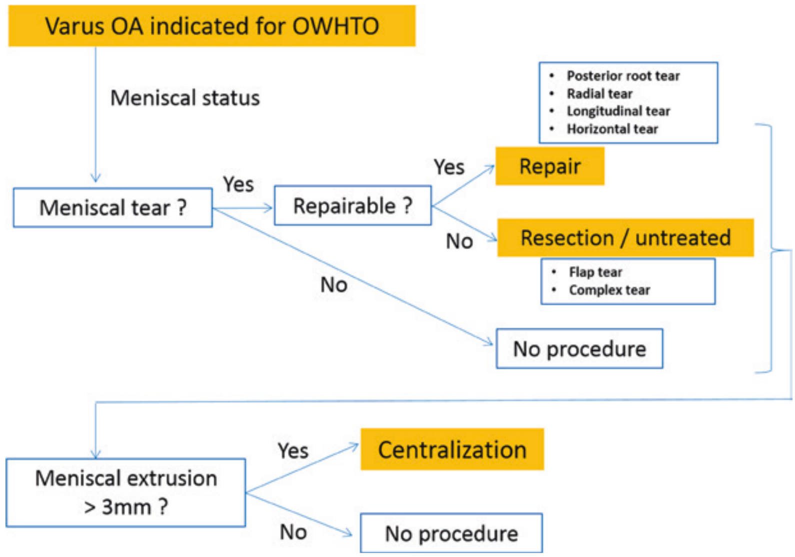

Fig. 1 Strategy for varus osteoarthritis indicated for open-wedge high tibial osteotomy (OWHTO)

angle (JLCA) are also measured. If the predicted mMPTA in the preoperative planning is 95° or greater for deformity correction with OWHTO alone, double level osteotomy is considered as a surgical option [23].

Surgical Technique

In order to obtain easier access to the posterior segment of the MM, release of the superficial medial collateral ligament is performed before arthroscopy. The medial proximal tibia is exposed by an oblique incision. The pes anserinus is cut and retracted medially. The superficial medial collateral ligament is released at the distal tibial side using a raspatorium. In cases with MMPRT, rough biplanar osteotomy lines are drawn and a tunnel outlet for pull-out repair is determined so that the outlet is positioned just lateral to the ascending line as proximal as possible (Fig. 2).

A standard arthroscopic examination is performed via routine anteromedial and anterolateral portals. Especially in cases with MMPRT, the anteromedial portal should be strictly made using a spinal needle so that the portal is positioned just proximal to the proximal border of the MM and posterior segment of the MM can be easily accessed (Fig. 3a, b). Other injuries including osteochondral lesion are managed according to the injury status.

Meniscus status is confirmed. Extrusion of the MM is confirmed by pushing the midbody of the meniscus out of the rim of the medial tibial plateau using a probe (Fig. 3c). Irreparable meniscus tears such as flap tear and degenerative tear are resected. Reparable meniscal tears such as longitudinal tear, radial tear and horizontal tear are repaired after centralization by the all-inside suture technique and/or the inside-out suture technique. Exceptionally, MMPRT repair without final fixation is performed before centralization (Fig. 4) [21]. Briefly, a Multi-use RetroConstruction Marking hook with the RetroConstrution ACL guide (Arthrex, Naples, FL, USA) is inserted from the anteromedial portal, with the marking hook placed over the attachment site of the MM posterior root. A 2.4-mm guide wire is inserted from the anteromedial aspect of the proximal tibia, and then a 6-mm-diameter tunnel is created with a cannulated drill. Three racking hitch knot sutures with SutureTapes (Arthrex) are placed at the torn edge of the meniscus using a Knee Scorpion Suture Passer (Arthrex). The sutures are then

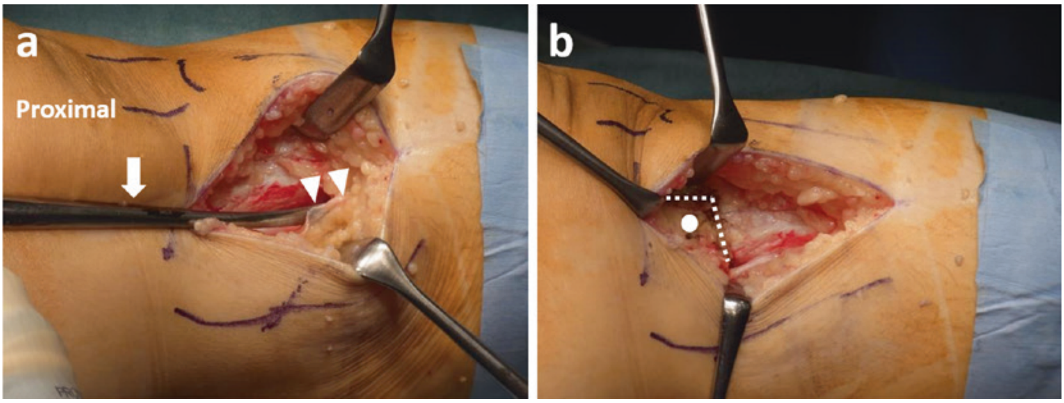

Fig. 2 Surgical procedure in a case with medial meniscus posterior root tear (MMPRT). **a** The superficial medial collateral ligament is released at the distal tibial side (arrowheads) using a raspatorium (arrow). **b** Rough biplanar osteotomy lines are drawn, and a tunnel outlet for pull-out repair is determined (circle) so that the outlet is positioned just lateral to the ascending line and as proximal as possible

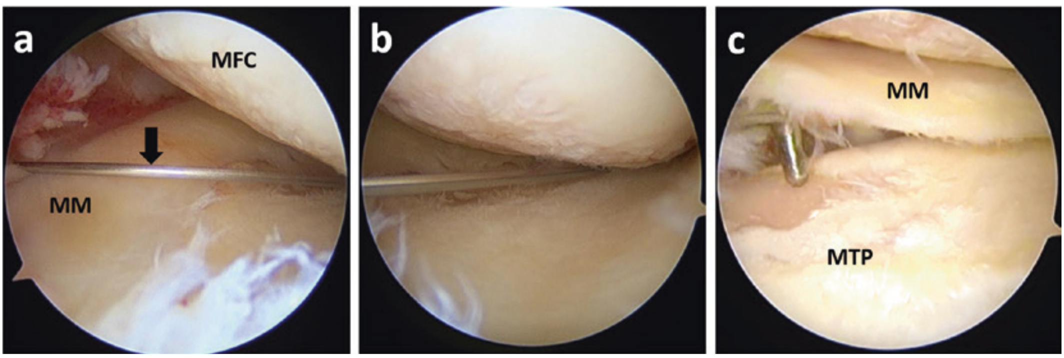

Fig. 3 The anteromedial portal is made using a spinal needle (arrow) strictly so that **a** the portal is positioned just proximal to the proximal border of the MM and **b** posterior segment of the MM can be easily accessed. **c** Extrusion of the MM is confirmed by pushing the midbody of the meniscus out of the rim of the medial tibial plateau (MTP) using a probe

shuttled transtibially through the tunnel to the anteromedial aspect of the proximal tibia. However, at this point, reduction of the torn posterior root to the anatomic insertion site as well as reduction of the meniscus extrusion is hardly achieved, especially in chronic cases (Fig. 4f).

Osteophytes at the medial femoral condyle and intercondylar notch are resected (if exist) using an osteotome, and the resected area is coagulated in order to prevent regrowth of osteophytes (Fig. 5). Resected osteophytes can be implanted into the osteotomy gap afterwards for accelerating bone union [24].

A midmedial portal is made with arthroscopic view from the anterolateral portal, 1 cm proximal to the MM and just anterior to the medial femoral condyle (Fig. 6a). Osteophytes at the medial tibial plateau are resected (if they exist) using an osteotome thorough the midmedial portal (Fig. 6b). An arthroscopic rasp, usually used for shoulder Bankart repair, is inserted through the midmedial portal. The meniscotibial capsule under the MM is then released from the medial tibial plateau for mobilization of the MM in order to ease reduction of the meniscus extrusion (Fig. 6c). This procedure is more critical in

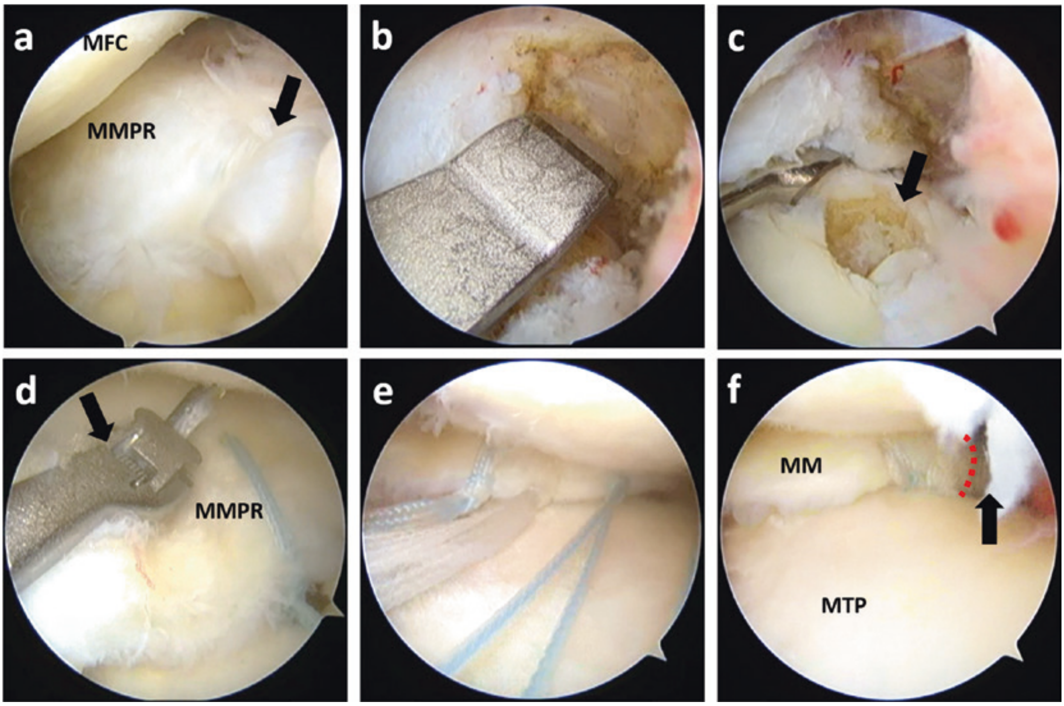

Fig. 4 MMPRT pull-out repair. **a** Chronic MMPRT with scar formation (arrow) is confirmed. MFC; medial femoral condyle. **b** A drill guide is placed over the attachment site of the MMPR and a guide wire is inserted. **c** A 6-mm-diameter tunnel (arrow) is created with a cannulated drill. **d** A knee Scorpion Suture Passer (arrow) is used and a racking hitch knot is applied. **e** Three SutureTapes are placed at the torn edge of the MMPR. **f** The sutures are introduced into the tunnel. However, at this point, reduction of the torn posterior root (dotted line) to the anatomic insertion site (arrow) is hardly achieved

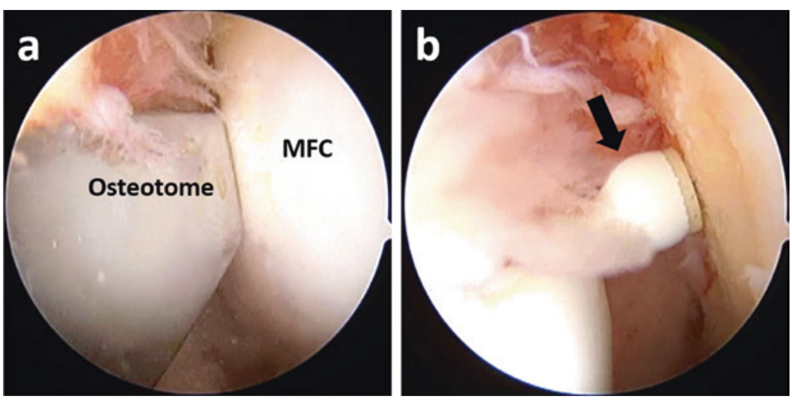

Fig. 5 **a** Osteophytes at the medial femoral condyle are resected using an osteotome. **b** The resected area is coagulated in order to prevent regrowth of osteophytes

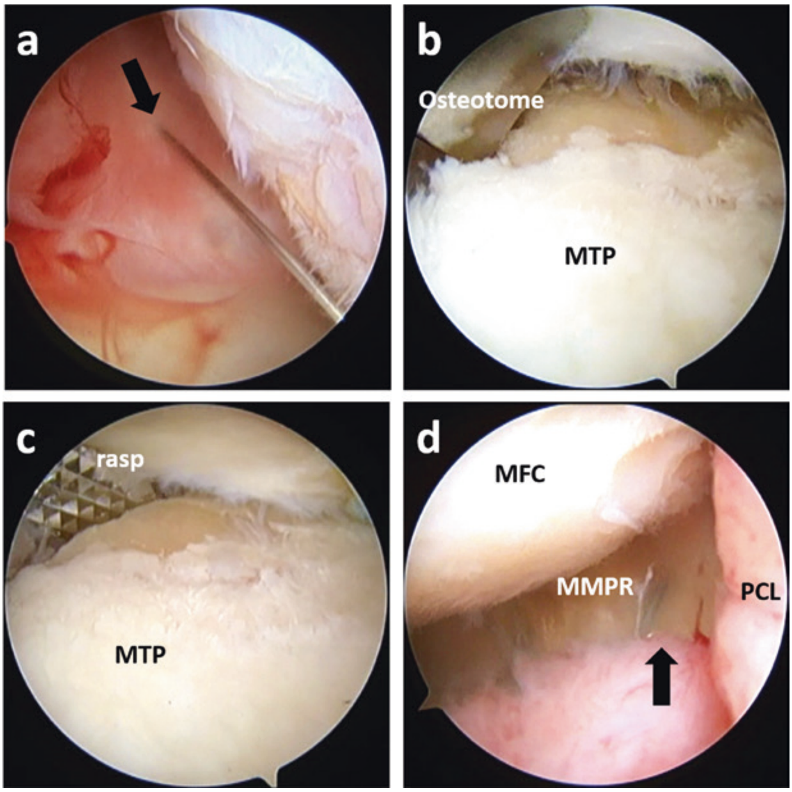

Fig. 6 **a** A midmedial portal is made 1 cm proximal to the MM and just anterior to the medial femoral condyle (arrow). **b** Osteophytes at the MTP are resected using an osteotome. **c** The meniscotibial capsule under the MM is released from the MTP using a rasp. **d** Sufficient release of the meniscotibial capsule eases reduction of the torn posterior root to the anatomic insertion site (arrow)

cases with MMPRT; releasing the meniscotibial capsule sufficiently from anterior to posterior eases reduction of the torn posterior root to the anatomic insertion site (Fig. 6d).

A 1.8 mm Q-FIX all suture anchor (Smith & Nephew, Andover, MA, USA) is inserted on the edge of the medial tibial plateau, as posterior as possible through the midmedial portal (Fig. 7a). The extruded MM is easily moved away and protected by a cannula for the anchor. A Micro Suture Lasso Small Curve with Nitinol Wire Loop (Arthrex) is then inserted through the midmedial portal. The tip of the Micro Suture Lasso penetrates the capsule from superior to inferior at the margin between the meniscus and the capsule, slightly anterior to the insertion point of the anchor (Fig. 7b). In cases with the MMPRT, the anterior penetration allows the midbody of the MM to move posteriorly, and consequently to ease reduction of the MMPRT. One strand of sutures is passed into the wire loop and the other limb of the wire loop is pulled to pass the suture from inferior to superior. The same procedure is repeated for another strand of the suture to create a mattress suture configuration.

Another Q-FIX Anchor is inserted on the edge of the medial tibial plateau, 1 cm anterior to the first anchor, and the same procedure is repeated (Fig. 7c). The passed sutures are then tied through the midmedial portal using a self-locking sliding knot. The extruded MM is reduced and centralized with this centralization procedure (Fig. 7d).

OWHTO is then performed. Approximately 4 cm distal to the joint line is defined as the starting point of the osteotomy, which allows

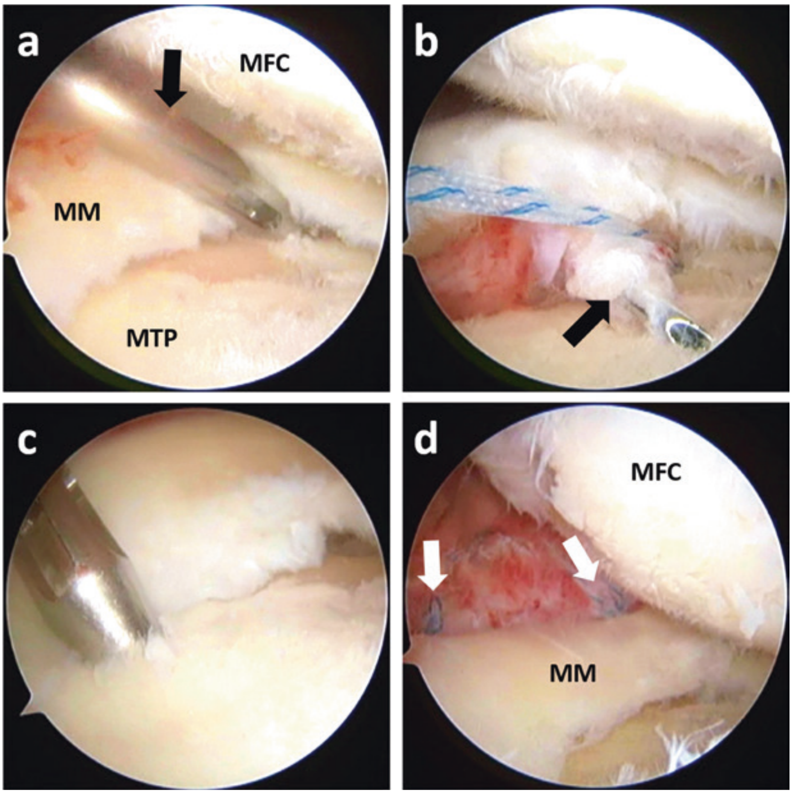

Fig. 7 **a** A Q-FIX anchor (arrow) is inserted on the edge of the MTP as posterior as possible. **b** A Micro Suture Lasso (arrow) penetrates the capsule from superior to inferior at the margin between the meniscus and the capsule, and a mattress suture configuration is created. **c** Another Q-FIX anchor is inserted 1 cm anterior to the first anchor, and the same procedure is repeated **d** The extruded MM is reduced and centralized with this centralization procedure (arrows)

positioning of the plate distally in order to reduce the risk of damaging anchors for centralization by screws. Two K-wires directed just proximal to the tibiofibular joint are inserted at the osteotomy level, and the osteotomy is performed using an oscillating saw and osteotome so that the osteotomy site approximately 10 mm from the lateral cortex remains intact. The separate ascending cut of the biplanar osteotomy is made 15 mm behind the tibial tuberosity, parallel to the long axis of the tibia. The osteotomy site is opened using several osteotomes. Finally, it is opened by a spreader while the limb alignment is monitored on fluoroscopy by checking the position of the alignment rod at the knee. Once the desired alignment (weight bearing line ratio at 57%) is obtained, the spreader is replaced with a wedge-shaped β-TCP (Osferion 60; Olympus Terumo Biomaterials, Tokyo, Japan) and osteophytes obtained arthroscopically with the intent of improving the mechanical properties of the osteotomy site and enhancing bone union [24, 25]. The Tomofix plate (DePuy Synthes, Solothurn, Switzerland) or the Tris Plate (Olympus Terumo Biomaterials) is used for fixation. In cases with MMPRT, the plate is placed as distal and posterior as possible, and during screw fixation, a dull rod is inserted into the tunnel for the MMPRT repair to avoid interference with the screw. After the plate is finally fixed, the sutures for the MMPRT are fixed with the ABS button (Arthrex) at 60° of knee flexion (Fig. 8).

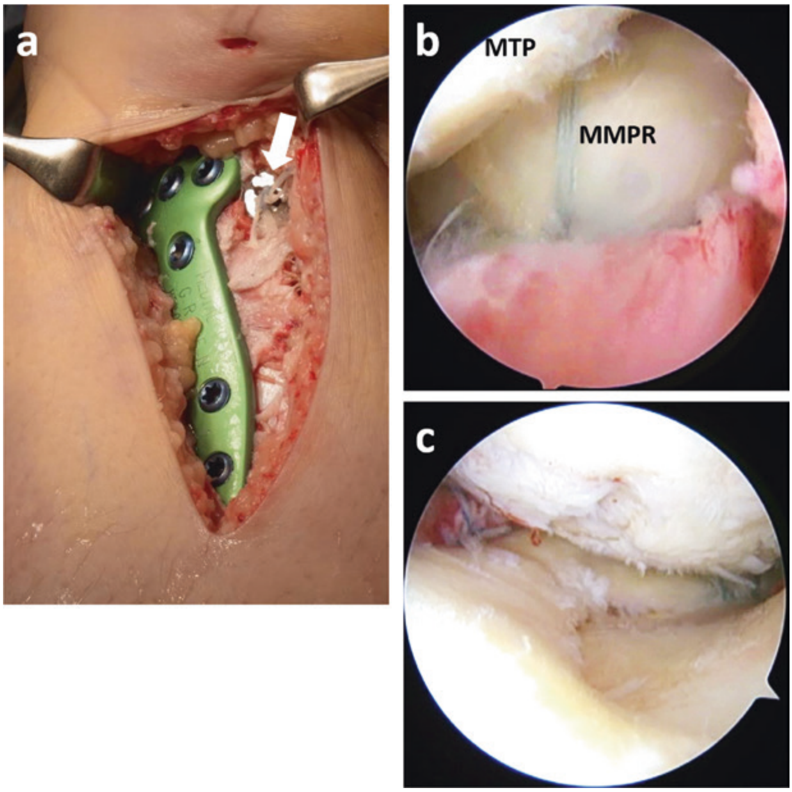

Fig. 8 **a** After HTO is performed, the sutures for the MMPRT are fixed with the ABS button. **b** The MMPR is reduced to the anatomic insertion site. **c** The extruded MM is reduced

Postoperative Rehabilitation

Range of motion exercise without restriction is encouraged immediately after the surgery. Partial weight bearing with a removable splint and crutches is allowed for the first 2 weeks. Full weight bearing is allowed as tolerated at 2 weeks after the surgery, but deep squatting over 90° is prohibited until 3 months.

Clinical Outcomes

A total of 20 patients who underwent OWHTO combined with arthroscopic centralization of the MM between 2014 and 2017 and who were followed up for 1 year were retrospectively reviewed. They comprised 10 male and 10 female patients with an average age of 59 years (range, 44–72 years) at the time of surgery. Preoperative Kellgren-Laurence classification grades were grade 2: 3 cases, grade 3: 10 cases and grade 4: 7 cases. Magnetic resonance imaging (MRI) was obtained preoperatively, and meniscus extrusion was measured on the coronal image showing maximum extrusion. Meniscal extrusion width, defined as the distance from the most peripheral aspect of the meniscus to the border of the tibia, excluding any osteophytes, was measured, and the mean MM extrusion width was 7.1 mm (standard deviation, 1.6 mm). Plain radiographs were obtained preoperatively and 1 year after the surgery. The femoro-tibial angle (FTA), the weight bearing line ratio, and the JLCA were measured on an AP long-leg weight-bearing radiograph. Knee extension angle, knee flexion angle, Knee Society (KS) Score, Lysholm Score, Knee injury and Osteoarthritis Outcome Score (KOOS) and Numerical Rating Scale (NRS) for pain during walking, rest, standing, stairs and sports were also evaluated preoperatively and 1 year after the surgery.

Clinical outcomes at 1-year follow-up after OWHTO combined with arthroscopic centralization of the MM were satisfactory (Table 1, Figs. 9, 10, and 11). The FTA was improved from 182° preoperatively to 172° at 1-year follow-up. The weight bearing line ratio was improved from 14% preoperatively to 59% postoperatively. The JLCA was significantly decreased from 4.5° preoperatively to 2.2° postoperatively (Fig. 9). There were no significant differences in knee extension and flexion angles. The KS Knee Score was improved from 70 to 94, and the KS Functional Score was improved from 68 to 94. All subscales of the KOOS were significantly improved (Fig. 10), and all items of the NRS were significantly improved as well (Fig. 11). Bone union was achieved in all cases, and there were no severe complications.

Table 1 Clinical and radiographic outcomes after OWHTO + MM centralization

N = 20	Preoperative	Postoperative[a]	P value
Femoro-tibial angle (°), mean (SD)	182 (2)	172 (2)	<0.001
% mechanical axis (%), mean (SD)	14 (12)	59 (5)	<0.001
Joint line convergence angle (°), mean (SD)	4.5 (1.4)	2.2 (2.4)	<0.001
Knee extension angle (°), mean (SD)	1.4 (2.3)	1.1 (1.5)	n.s.
Knee flexion angle (°), mean (SD)	143 (6)	143 (8)	n.s.
Knee society score, mean (SD)			
Knee score	51 (11)	94 (8)	<0.001
Functional score	70 (15)	94 (8)	<0.001
Lysholm score, mean (SD)	68 (16)	94 (5)	<0.001

SD, standard deviation
[a]Postoperative status at 1-year follow-up

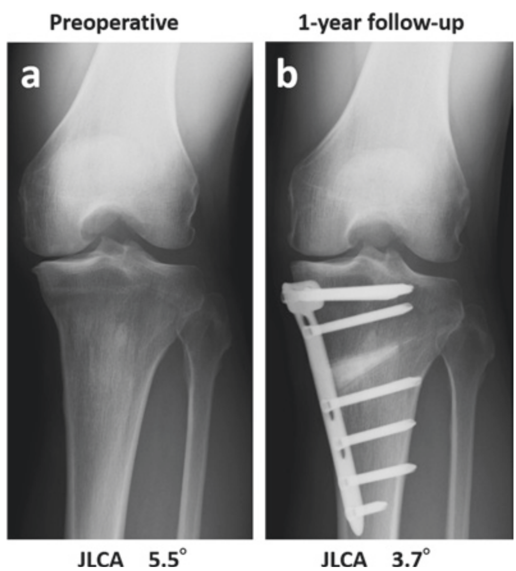

Fig. 9 **a** Preoperative and **b** 1-year follow-up radiograph as a representative case. The JLCA decreased from 5.5° preoperatively to 3.7° at 1-year follow-up

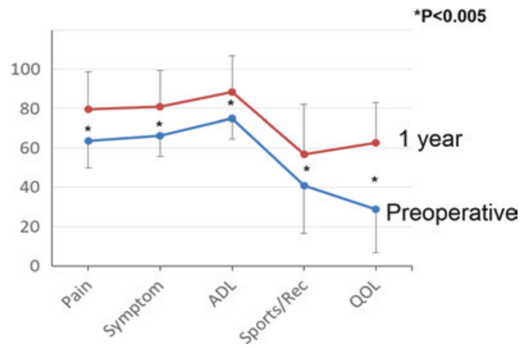

Fig. 10 KOOS preoperatively and at 1-year follow-up

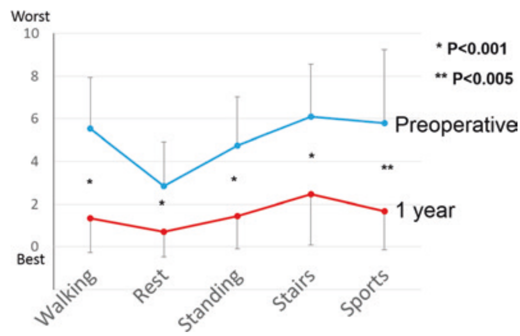

Fig. 11 NRS preoperatively and at 1-year follow-up

Discussion

HTO is an effective treatment for the medial unicompartmental knee OA, and favorable outcomes after isolated HTO have been reported

[1, 26]. On the other hand, as long-term results are still not satisfactory, several combined procedures with HTO have been reported in order to improve clinical results as well as to decrease the conversion rate. The most reported combined procedure with HTO is a bone marrow stimulation for cartilage defects, such as microfracture, drilling and abrasion. However, most studies have shown no difference between isolated HTO and HTO combined with the bone marrow stimulation, and its additional effects are limited [27, 28]. Other procedures could be osteochondral autologous transfer [29], autologous chondrocyte transplantation [30], stem cell transplantation [31, 32] and platelet-rich plasma [33], and good clinical outcomes have been reported after HTO with these procedures. However, there have been very few studies that compare isolated HTO versus HTO with the combined procedure prospectively and have clearly indicated the effectiveness of the combined procedure with high-level evidence. Thus the effectiveness of the combined procedures is still controversial. On the other hand, Harris et al. [34] reported in a systematic review that HTO with articular cartilage surgery had a significantly greater survival rate (97.7%) than isolated HTO (92.4%) at 5 years of follow-up, suggesting that combined cartilage treatment could improve the survival rate after HTO.

Extrusion of MM has been reported to be an independent risk factor for progression of OA [11, 12], and extrusion of MM has been observed in most cases indicated for MOHTO. We have developed a novel procedure for meniscus extrusion called arthroscopic centralization [17, 18], and have shown that centralization of the MM reduced meniscus extrusion and delayed progression of medial compartment OA [22]. Although this is just a 1-year follow-up, our current case series also showed that clinical results after OWHTO combined with centralization of the MM were comparable to those after HTO with combined procedures. It is also particularly notable that the JLCA was significantly decreased in this case series. Lee et al. [35] reported that the difference in the JLCA from before to after HTO correlated with both correction amount and correction error, i.e., the difference in the JLCA became larger in the case of over-correction (with a weight bearing line ratio >67%). On the other hand, our results have shown a significant decrease of the JLCA, in other words, medial joint space widening, despite the aiming weight bearing line ratio of 57% (and the resultant weight bearing line ratio of 59% because of decreased JLCA). This is probably because not only reduction of the extruded MM itself widened medial joint space, but also restored load distributing function of the MM by centralization promoted cartilage repair. Although further follow-up is necessary, improvement of the long-term outcomes could be expected.

Limitations of this case series include a relatively small number of patients, short-term follow-up, no evaluation by second look or MRI postoperatively, and no comparison with the control group (isolated HTO). Further investigations regarding longer follow-up, evaluation by arthroscopy and MRI, and prospective comparative studies are definitely required.

Summary

Detailed surgical procedure of minimum correction OWHTO, aiming for neutral alignment, combined with arthroscopic centralization of extruded MM was introduced. Clinical results at 1-year follow-up were comparable to those after HTO with previously reported combined procedures, with a significant decrease in the JLCA. This procedure could expect better long-term clinical and radiographic outcomes as well as a decrease of possible adverse effects by valgus alignment.

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Distraction Arthroplasty for the Advanced OA

Nobuo Adachi, Masataka Deie and Mistuo Ochi

Abstract

Articular cartilage has a poor healing capacity due to its lack of vessels, nerve supply, and isolation from systemic regulation, if cartilage injury is not diagnosed accurately or not treated properly, it gradually deteriorates by causing kissing cartilage lesions or degeneration of neighboring tissue, leading to secondary osteoarthritis. Even with the recent progress in orthopaedic surgery, cartilage injury remains one of the most problematic diseases. Especially, treatment of advanced OA in younger patients have been challenging, because TKA cannot be indicated due to its high revision rate for such patients. We have performed "distraction arthroplasty" with a newly developed articulated distraction arthroplasty device which were invented by co-author Mitsuo Ochi, in conjunction with microfracture technique. In this chapter, we summarize the previous basic researches on distraction arthroplasty and describe the surgical procedure and clinical outcomes.

Keywords

Knee · Osteoarthritis · Distraction arthroplasty · Articular cartilage · Treatment

Introduction

Articular cartilage injury can be caused by acute or repetitive trauma, osteochondritis dissecans, rheumatoid arthritis, osteoarthritis, or various other conditions. The wide spread of sports activities in every generation and the increased number of elderly people provide us with many opportunities to treat patients with cartilage injury.

Articular cartilage is hyaline cartilage that mainly consists of a small number of chondrocytes and a surrounding dense extracellular matrix. Because articular cartilage has a poor healing capacity due to its lack of vessels, nerve supply, and isolation from systemic regulation, if cartilage injury is not diagnosed accurately or not treated properly, it gradually deteriorates by causing kissing cartilage lesions or degeneration of neighboring tissue, leading to secondary osteoarthritis. Even with the recent progress in orthopaedic surgery, cartilage injury remains one of the most problematic diseases. Despite a variety of treatments for articular cartilage defects, such as drilling, microfracture

N. Adachi (✉) · M. Deie · M. Ochi
Department of Orthopaedic Surgery, Graduate School Biomedical and Health Sciences, Hiroshima University, 1-2-3 Kasumi, Minami-ku, Hiroshima 734-8551, Japan
e-mail: nadachi@hiroshima-u.ac.jp

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techniques, soft tissue grafts, osteochondral grafts, and chondrocyte implantation, none has managed to repair a large osteochondral defect with long-lasting hyaline cartilage. Until now, there has been no well-established gold-standard procedure for cartilage injury [1–10].

Among the treatment of cartilage injuries, treatment of advanced OA in younger patients have been challenging, because TKA or osteotomies (HTO or DFO) cannot be indicated due to younger age or advanced total type of OA. Although drilling or microfracture have been performed as first-line treatment for diffuse OA, disadvantages of those procedures are clinical improvement for limited short periods as described several meta-analysis or systematic review.

We have performed "distraction arthroplasty" with a newly developed articulated distraction arthroplasty device in conjunction with microfracture technique. The indications for distraction arthroplasty were as follows: younger patients with high activity who are not satisfied with conservative treatments, end-staged OA (Kellgren-Lawrence grading 3 or 4), severe degenerative change with or without angular deformity on plain radiogram, and patients whom osteotomies or arthroplasties cannot be indicated. Our colleague have reported basic researches on distraction arthroplasty and preliminary clinical outcomes of this procedure.

Basic Research on Distraction Arthroplasty for Cartilage Defect of the Knee

There has been very a few basic researches for the distraction arthroplasty using animal models. van Valburg reported that joint distraction which allowed joint motion using external fixator accomplished good results for canine OA model in 1999 [11]. In 2005, Kajiwara et al. evaluated the efficacy of joint distraction which can allow joint motion after drilling for the osteochondral defect which was in the weight bearing area of the rabbit knee joint [12]. A full thickness osteochondral defect on the weight bearing area of medial condyle was treated with drilling followed by 1.5 mm joint distraction using the external fixator to decrease the compression force. Having this external fixator, the rabbits can move their knee joint to some extent. The authors evaluated the repaired tissue grossly and histologically at 4, 8, 12 weeks after the surgery. As results, they found significantly better cartilaginous repair in the experimental group compared to the control group at 8 and 12 weeks. The conclusion of this study was that combination of subchondral drilling and joint distraction with motion by external fixator which allows joint motion enhanced cartilaginous repair for the fresh osteochondral defect in the weight bearing area of the rabbit knee joint.

More recently, Harada et al. investigated the combination therapy of intraarticular injection of MSCs (mesenchymal stem cells) derived from bone marrow and joint distraction for the chronic osteochondral defect models in the rabbit weight bearing area of the knee [13]. The osteochondral defects were created 4 weeks before the several treatments. The treatments were divided into 6 groups as control group, MSC group, distraction group, distraction + MSC group, temporary distraction group, and temporary distraction + MSC group. Intraarticular injections of MSC were done in the MSC groups. Articulated distractions were applied in the distraction groups. Temporary distraction groups received joint distraction only for first 4 weeks. As results, the authors reported that histological scores in the distraction + MSC group were significantly better than those in the control, MSC, and distraction groups at 4 and 8 weeks. At 12 weeks, there was no further improvement in the repair tissue. However, more interestingly, temporary distraction + MSC group demonstrated very good cartilaginous repair than other groups showing hyaline like cartilage regeneration and good osteochondral junction. This study showed future possibility of the combination therapy with joint distraction and stem cell therapy.

Surgical Procedures, Postoperative Rehabilitation, and Second-Look Arthroscopy

Parallel to those basic studies, we have begun the clinical application of the articulated distraction therapy for the relatively young patients with advanced OA. Inclusion criteria was grade 3 or 4 OA on the Kellgren-Laurence grading scale at 1 or 2 compartments of the FT joint [14].

Surgical procedure began with usual arthroscopy and drilling or microfracture for the cartilage injury. Drilling or microfracture were performed at 4 or 5 points per square centimeters based on the usually recommended procedures. Bleeding from the drilled or microfractured holes was confirmed.

As for the distraction device, our senior author (M.O.) developed a new distraction arthroplasty external fixator for the knee joint (Meira, Nagoya, Japan). The detailed surgical procedures were described in the previous report by Deie et al. [14] Briefly, two 6-mm pins for distal femur and two 6-mm pins for proximal tibia were inserted after considering the appropriate motion center according to the manufacturer's instruction. Then, femoral pins and tibial pins were connected with distraction arthroplasty device (Fig. 1). While checking the width of joint using fluoroscopy, both device were fixed, and range of motion of the knee joint was confirmed. Postoperative rehabilitation is as follows. Active and passive ROM exercises were started from 1 day after the surgery with the instruction by a physical therapist. Two weeks postoperatively, partial to full weight-bearing was allowed depending on the patient's pain tolerance. Three months after the operation, second-look arthroscopy and distraction arthroplasty device removal were performed. Manipulation under arthroscopy was performed at the time of device removal if necessary.

Clinical Outcomes

The preliminary results was published in 2007 by Deie et al. [14] They treated 6 patients (age: 42–58) with advanced OA using distraction arthroplasty. Fixation periods in this study ranged from 7 to 13 weeks. The follow-up periods were from 1 to 3.5 years. They reported that Japanese Orthopaedic Association Score significantly improved postoperatively, and average joint space also increased compared to preoperative values (Figs. 2, 3, 4). They proposed several mechanism of efficacy of the procedure. First of all, this distraction device could protect newly formed cartilage after microfracture or drilling by widening the joint space. Second, articulated distraction device which allowed joint motion could enhance cartilage regeneration. Third, joint contracture due to contractured ligament or joint capsule could be elongated by distracting the knee joint. Those could be one of the reasons for pain or range of motion improvement. Recently, we have evaluated the mid-term (average: about 6 years) clinical outcomes of distraction arthroplasty for the OA. As preliminary outcome, joint space was widened, KOOS pain subscale and over all clinical score were significantly improved. Those outcomes will be published very soon.

Future Perspective

There have been several aspects which are not certain and should be clarifies in the future studies.

First of all, we have not known the appropriate distraction force and optimum loading yet. Second, the appropriate fixation periods must be determined. Apparently, 12 weeks fixation is too long for the patient for their daily life, because with this external fixation devices applied both sides of the knee, patients' life style is severely restricted. Therefore, more concise distraction device must be developed, hopefully with half pin usage. In 2015, Kamei G et al. proposed new distraction arthroplasty device using magnetic force. They used cadaveric knees those were embalmed by Thiel's methods and measured joint space widening, contact pressure of medial and lateral compartments with weight bearing condition [15]. They found that that device using magnetic force maintained continuous

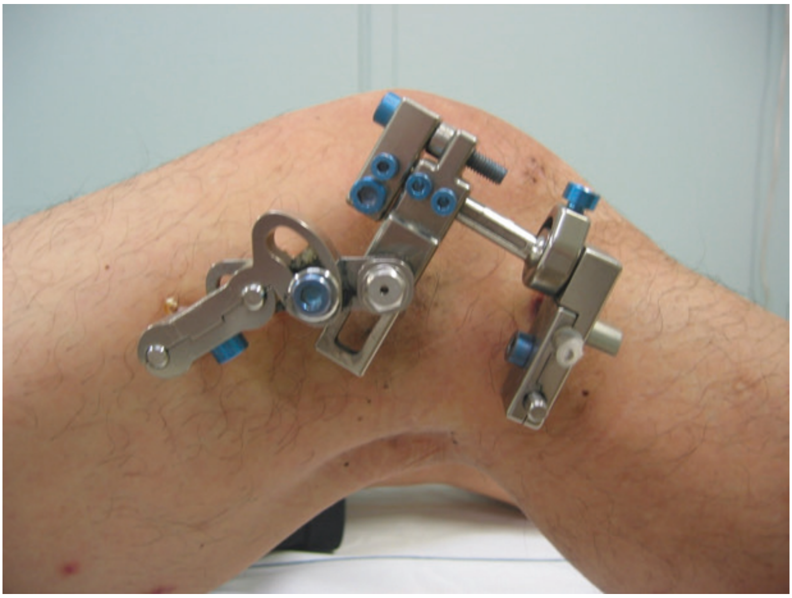

Fig. 1 Distraction device

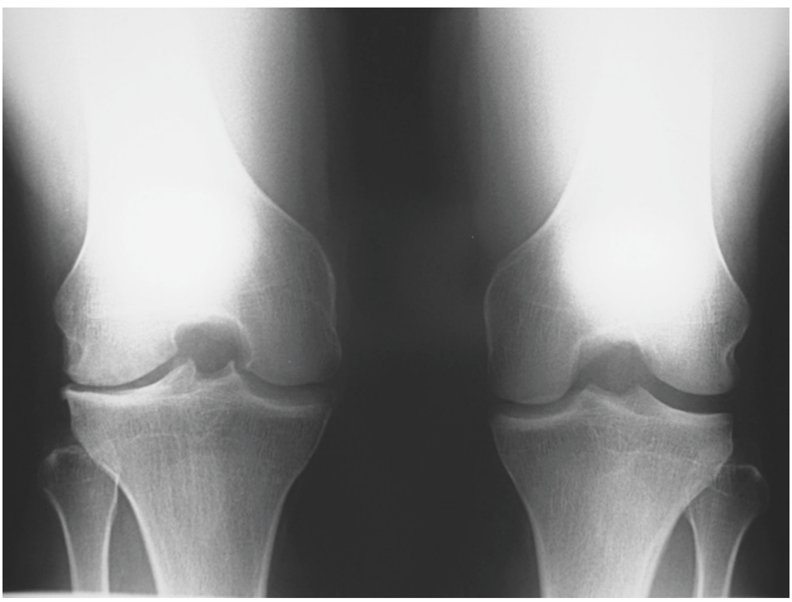

Fig. 2 A 33-years-old male, 18 years after lateral meniscectomy (right knee). Preoperative radiographs

distraction tension and enabled almost full range of motion.

The most important future combination is articulated distraction device and meniscal treatment. Usually, advanced OA patients' meniscus are severely damaged or more often disappeared. Without good meniscal function, long-term clinical outcome cannot be expected. Meniscal allograft or other meniscal regeneration procedure using appropriate scaffold with or without stem cell therapy is definitely necessary.

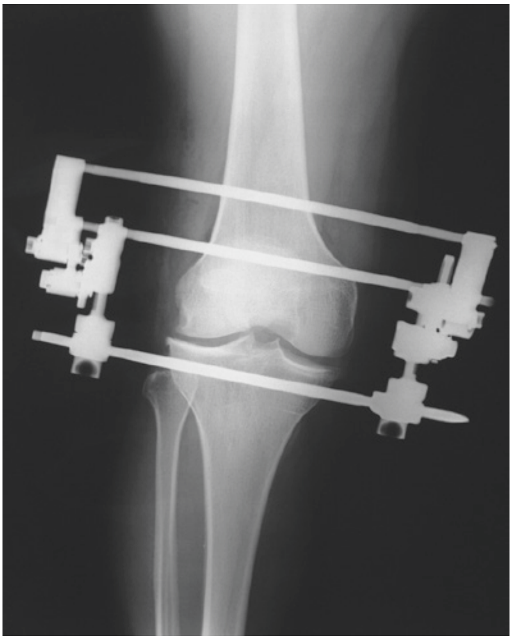

Fig. 3 Plain radiograph while distraction

Fig. 4 8 months after surgery

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