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Integrated studies master's thesis

Advancement of Anterior Cruciate Ligament (ACL) Reconstruction

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1. Abbreviations

ACL - anterior cruciate ligament

PCL- posterior cruciate ligament

BTB- bone-tendon-bone

BPTB- bone-patellar tendon-bone

QT- quadriceps tendon

HT- hamstring tendon

AKP- anterior knee pain

ROM- range of motion

IB- internal bracing

PRP- platelet rich plasma

BMAC- bone marrow aspiration concentrates

AM bundle- anteromedial bundle

PL bundle- posterolateral bundle

DIS- Dynamic intraligamentary system

2. Keywords

ACL

Reconstruction

Graft

Tendon

Joint

Arthroscopy

3. Summary

The anterior cruciate ligament (ACL) injury is one of the most common orthopedic injuries, affecting especially athletes and patients participating in sports. As a stabilizer of the knee, especially in anteromedial movements, the ACL is an essential factor for maintaining joint stability. This thesis focuses on the most used grafts for ACL reconstruction: bone-patellar tendon-bone (BPTB), hamstring tendon, quadriceps tendon, allografts and synthetic grafts. Each graft offers its specific advantages and disadvantages in terms of revision risk, success rate, and post-surgical quality of life. Additionally, this thesis will examine the double-bundle technique and isometric considerations during surgery. A historical review of graft development and surgical advancements will also be presented. Through a comparison of modern graft options, alternative methods and patient outcomes, the aim is to identify the current gold standard for ACL reconstruction.

4. Methods

This review includes a range of methodologies to provide a comprehensive overview of ACL reconstruction and its graft options to define the gold standard. The included studies comprised clinical trials, systematic reviews, meta-analyses, and narrative reviews trying to find viable and relevant information on different aspects of graft types, synthetic and allografts and their advantages, disadvantages and outcome.

For the historical overview, literature from approximately 1800-2024 was used to describe the evolution of ACL surgical techniques, graft types and biomechanical principles. For the review of contemporary practices, a timeframe of the past 20 years was selected to capture recent advancements, trends, and innovations in ACL reconstruction techniques and outcome.

The research was conducted using search strategies across multiple academic databases, books, medical journals, and websites including PubMed, Google Scholar, Elsevier, the Cochrane Library, Amboss and Doccheck . Key terms such as *"graft," "ACL reconstruction," "bone-patellar tendon-bone," "hamstring tendon," "quadriceps tendon," "arthroscopy," "ACL augmentation,"* and *"anterior cruciate ligament reconstruction"* were applied to find relevant literature. Filters were applied to limit results to peer-reviewed articles, publications in English or German, and studies which seemed to be relevant to the research.

Inclusion criteria focused on studies providing detailed information about graft selection, surgical techniques, clinical outcome such as success and revision rates, and postoperative considerations. Studies included clinical trials, meta-analyses, systematic reviews, and case studies. Literature excluded from the analysis comprised outdated articles, broadly focused reviews with limited relevance to ACL reconstruction, and non-peer-reviewed materials.

The data was extracted by using a structured approach, going by topic with the review objectives. Relevant information was categorized and synthesized under specific themes:

- Clinical Outcome: Success rates, stability, complications (e.g., graft failure, donor site morbidity), and postoperative challenges.
- Graft Properties: Selection criteria, biomechanical characteristics, comparisons, and the identification of a potential "gold standard" graft.
- Rehabilitation and Recovery: Recovery timelines, return-to-sport rates, and rehabilitation duration.

- Surgical Details: Techniques such as single-bundle vs. double-bundle procedures, graft fixation methods, and the role of graft augmentation.

The limitations of this review include the amount of literature and studies which impeded the process of extracting the most important material and the latest studies. For some topics such as graft augmentation and allografts the literature is scarce which presents the issue of limitations to perform a quantitative analysis of studies. There is a need for more studies and clinical trials in order to determine specific outcomes of specific grafts. Another issue is the variance of the graft types. This makes the comparison vague since grafts are prepared differently and fixed with various different materials.

5. Introduction

The anterior cruciate ligament (ACL), historically referred to as *ligamentum genu cruciata*, was first described by a Greek physician Claudius Galen in 170 A.D. Galen recognized the ACL as an important structure providing support to the knee joint, preventing abnormal movements.(1) However, it wasn’t until centuries later that this ligament became a field of interest and therefore more researched and focused on. The ACL’s role in stabilizing the knee joint has led to its significance, particularly in sports medicine, as a common site of injury that requires most often surgical intervention.

ACL tears are among the most often encountered knee injuries, especially in young and physically active individuals. These injuries typically occur due to high-impact forces or sudden movements during sports or everyday activities. The global incidence of ACL ruptures is approximately 68.6 per 100,000 individuals per year, and in the United States alone, approximately 1 in every 3,500 individuals will encounter this injury, making ACL tears one of the most prevalent orthopedic injuries.(2) Sports such as football, soccer, basketball, and skiing, which involve sudden directional changes, jumps, and landings, are often associated with higher risks of ACL injuries. Additionally, female athletes are at a higher risk of ACL injuries, which has been linked to several factors such as muscular imbalances, where the quadriceps may dominate over the hamstrings, as well as hormonal variations, particularly during the pre-ovulatory phase of the menstrual cycle.(3) Other risk factors contributing to ACL injuries include a high body mass index (BMI), a smaller femoral notch leading to impingement of the ligament, joint hypermobility, ligament laxity, and a history of previous ACL or posterior cruciate ligament (PCL) injuries.(3,4)

Anatomically the ACL originates from the medial aspect of the femur's lateral condyle and inserts at the anterior intercondylar area of the tibia, near the tibial spine. Structurally, the ACL is composed of dense connective tissue, comprising two bundles: the anteromedial (AM) and the posterolateral (PL) bundles. Together, these bundles form a ligament with a diameter ranging from 7 to 12 mm and a length of approximately 32 mm in a fully extended state. The ACL plays an important role in preventing anterior displacement and excessive internal rotation of the tibia relative to the femur. Consequently, ACL injuries often occur when these movements exceed the ligament's capacity to stabilize the knee, such as during hyperextension or pivoting motions. (3,5,6)

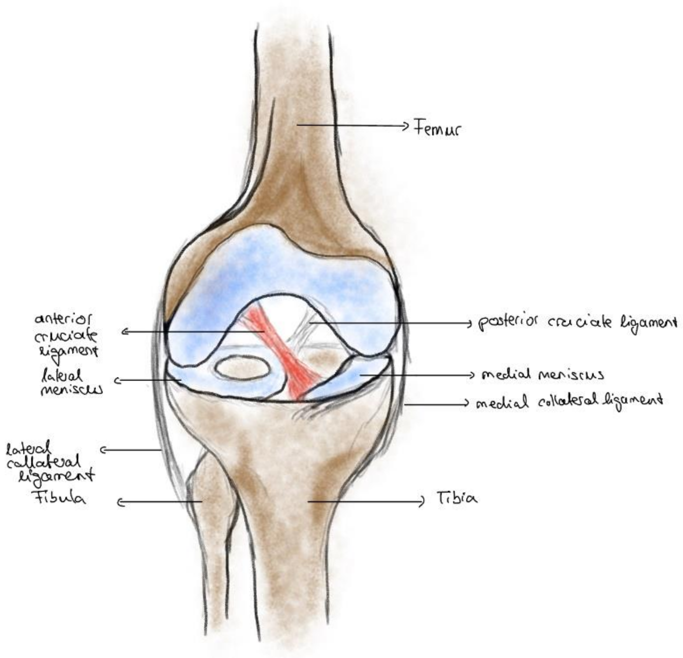

Figure 1- Normal knee anatomy

The typical mechanism of injury involves abnormal or forceful motion, such as jumping and landing unusually, sudden deceleration, or abrupt changes in direction during sports activities. In many cases, individuals report hearing a distinctive "popping" sound at the moment of injury, which is often followed by immediate pain, joint swelling (hemarthrosis), and instability, commonly referred to as the knee "giving way." Examination may reveal signs of joint line tenderness, especially if the meniscus is also injured, and there is typically pain associated with movement and a limited range of motion.(3,7)

Diagnosis of an ACL tear involves several clinical tests, including the anterior drawer test, the Lachman test, and the pivot-shift test. Imaging studies, particularly magnetic resonance imaging (MRI), are often used to confirm the diagnosis. MRI has become the preferred imaging modality, given its sensitivity of approximately 86% and a specificity of 95%, which allows for an accurate assessment of the extent of the injury.(3,7) Arthroscopy is the gold standard for diagnosing partial or complete ACL tears.

For individuals with a complete ACL rupture, surgical reconstruction is generally recommended, particularly for those who are young, active, or participate in sports in which knee stability is needed. Additionally, ACL reconstruction may be indicated for older individuals who require a stable knee for daily activities and want to avoid the risk of secondary injuries such as meniscal tears or chondral damage, which can occur in the absence of a stable joint. Preoperative physical therapy is often advised to improve the patient's range of motion and muscle strength prior to surgery, which can contribute to a better postoperative recovery.(8,9)

Several types of grafts are available for ACL reconstruction, each having their specific benefits and disadvantages. The most common graft options include autografts, such as the bone-patellar tendon-bone (BPTB), hamstring tendon, quadriceps tendon grafts, as well as allografts and synthetic grafts. The choice of graft depends on the patient’s individual needs, the surgeon's expertise, and the desired postoperative outcomes. Each graft has specific properties in terms of recovery time, success rate, and the long-term quality of life.(9)

The primary goal of this thesis is to provide a literature analysis of the various graft types used in ACL reconstruction, focusing on their specific advantages, success rates, and potential complications. Furthermore, alternative and additive approaches such as graft augmentation will be reviewed. The development of ACL reconstruction techniques over time, especially in the 20th and 21st centuries, will also be reviewed, and therefore, trying to explain how current grafts and surgical techniques have evolved.

Moreover, this thesis will address the various techniques used alongside these grafts, such as double-bundle reconstruction, graft isometry, and anatomical graft positioning, as well as the use of biological augmentation to enhance healing and reduce complications. Understanding the differences between these methods will help in identifying which approaches provide the best functional recovery and long-term stability for patients. By comparing modern graft options such as BPTB, hamstring tendon, quadriceps tendon, allografts, synthetic grafts, and alternative methods, the thesis aims to define the gold standard of ACL reconstruction.

6. History

The history of the anterior cruciate ligament (ACL) and its treatment is marked by significant contributions from various pioneers in the field. From the first ever description to the newest modern techniques will be described in this section.

Claudius Galen (129-199 A.D.) was the first to describe the ACL, referring to it as the ligamentum genu cruciata. Galen characterized it as a crucial structure supporting the knee joint against abnormal movements. His early observations laid the groundwork for future studies of the ligament's anatomy and function. (10)

The Weber Brothers (1836) in Göttingen made notable advancements in understanding the biomechanics of the ACL. They provided the first biomechanical analysis of the ligament, illustrating its anatomy and emphasizing its role in stabilizing the knee joint in the anteroposterior plane. They identified the anatomical insertion points and positions of the ligaments within the joint, as well as other structural components essential for knee stability. (10)

Bonnet (1845) conducted the first cadaver studies that examined the mechanisms of ACL injuries. His findings indicated that ACL ruptures primarily occur at the femoral insertion site. He noted the distinct popping sound often associated with ACL tears and observed that hemarthrosis frequently accompanies such injuries. Bonnet was also the first to describe the phenomenon of subluxation in relation to ACL injuries. To aid recovery, he recommended using an active motion machine and immobilizing the knee joint with a hinged cast to provide additional stability during the healing process. (1)

Georgios Noulis (1875) introduced the Lachman test, a critical diagnostic tool for assessing ACL integrity, which remains a standard part of clinical examination today. (1)

Robson (1895) detailed surgical intervention for ruptured ACLs and posterior cruciate ligaments (PCLs) following a workplace injury. He stitched the ACL using catgut, achieving initial stability, and reported no major concerns eight years post-surgery. His cadaver studies further clarified the mechanisms behind ACL injuries, reinforcing the idea that ruptures commonly occur at the femoral insertion site. (1,10,11)

Goetjes (1913) reviewed 30 cases, underscoring the importance of tailoring therapy based on patient history and the nature of the injury. He outlined that diagnosis could be made through X-rays, revealing signs of injury or joint dysfunction. If the diagnosis was unclear, conservative treatment was advised. For partial ruptures, he recommended conservative measures like cooling, immobilization, and joint puncture. In cases of complete ACL tears, he suggested suturing the ligament together if it was long enough; otherwise, a tendon lengthening technique was to be employed. (10)

Grekow (1914) introduced the use of a free fascia latae strip as a graft material for ACL reconstruction. (10,11)

Hey Groves (1917) proposed using an entire fascia lata strip from the iliotibial tract for reconstruction. His technique involved drilling holes through the femur and tibia to suture the fascia with the tibial periosteum. However, he later noted that this method decreased lateral stability due to the removal of the fascia. (1,10,11)

Perthes (1926) argued that ACL reconstruction should mimic the natural design intended for joint stability. He recommended an osteotomy of the patella and a slitting of the patellar tendon when the ACL tore close to the femur. The tendon would then be repositioned using aluminum bronze wire, facilitating the creation of a new ligament-like structure. (1,11)

Zu Verth (1932) focused on patellar tendon replacement as a viable option for ACL reconstruction. (10)

Galeazzi (1934) was the first to use the hamstring graft and the patients' knees were put into casts for 4 weeks and then allowed partial weight-bearing. The graft was passed through a 5 mm drilled tunnel of the tibia and then pulled through a drilled tunnel placed at the lateral femoral condyle and fixated to the periosteum. (1,11)

Campbell (1936) was one of the first using the patella and quadriceps tendon to reconstruct and repair the ACL which became a technical base for future approaches(1,11).

Lindemann (1950) reestablished the usage of the gracilis and semitendinosus muscles as an alternative graft option which was originally used by A. Edwards. In the 60s the hamstring grafts regained popularity because of fewer donor site complications. Therefore, Du Toit established the Lindemann procedure in which the gracilis tendon is pulled through the joint and fixed to the tibia. (11)

In the 60s and 70s the focus of surgical approaches started to shift from repairs to intraarticular graft reconstructions. Campbell (1936) used the patella tendon to reconstruct the ACL. This technique was then refined and improved by the following people:

K. Jones (1963) created the BPTB graft requiring several attempts to reconstruct the ACL adequately. The graft was made from the middle third of the patella tendon and the bone plug taken from the whole patella which was then passed through the Hoffa bursa and then through the femoral tunnel. (1,12)

Brückner (1966) also used the medial patellar tendon but passed it through a tibial and femoral tunnel. The femoral tunnel was used as an all-inside tunnel. Furthermore, he described that the tibial tunnel can be also used with a bone plug, rather than only a tendon. (11)

Trillat continued to use the BTB technique but was able to improve the graft while preserving the attachment of the distal end of the patella. Not much later Franke was able to utilize a free graft, and this approach was then defined as the gold standard until the late 20th century. (11)

J. Feagin (1976) criticized the practice of primary suturing due to the high rate of non-healing and complications associated with this technique. The ACL repair and suturing was facing a lot of backlash during the 70s and therefore the graft reconstruction was able to gain in popularity. (10,11)

Macintosh and Marshall (1979) invented, the nowadays known, over-the-top repair, therefore they used the quadriceps tendon and passed through a tunnel placed over the femoral condyle, sutured and fixed with a metal clip and then brought to Gerdy's tuberosity(11). Blauth (1980s) was able to create a graft of the quadriceps tendon combined with a bone plug which was then converted by Fulkerson into a soft tissue graft in the 90s (1).

In 1988 Friedmann (1) used the hamstring graft in a fourfold preparation and therefore enhanced the technique used by Galeazetti. In the 90s the hamstring graft was then again improved, by using four stranded grafts and experimental grafting techniques, by Howell, Rosenberg and Pinczewski.(1) Furthermore fixation methods such as interference screws were developed and still have nowadays their relevance in ACL reconstruction.(1)

In the 80s arthroscopic surgery was invented by Robert Jackson and David Dandy, which made the ACL reconstruction open for new inventions and approaches(1). Dandy performed the first ACL reconstruction with a carbon fiber graft combined with a lateral extraarticular tenodesis(11). This approach, with carbon fiber as a graft, soon failed because of the high complications and revision rates. In earlier days Kennedy and Willis created the approach of ligament augmentation with synthetic material(11). During the rest of the century until nowadays, synthetic grafts appeared and disappeared due to the high rates of complications until LARS was introduced(11), which is nowadays the most current graft option as a synthetic graft. Also, allografts gained in popularity during the 70s and 80s. In 1930 Bircher used a kangaroo tendon to replace the ACL and implemented an active rehabilitation program which included early mobilization instead of using casts and immobilization for patients undergoing ACL reconstruction(10). In 1984-1986 Shino then introduced the usage of allografts with good outcomes, therefore leading to a usage in the minority of patients(10). Due to the infectious risk of HIV and hepatitis, interest in allografts decreased and they are still only used in the minority of patients.

In the 21st century autografts, especially BPTB and hamstring tendon grafts have gained the most popularity. The BPTB is still seen as the gold standard and is most widely researched. The quadriceps tendon has regained interest in 2010 and still used but less commonly than BPTB and HT grafts. (1,10,11)

7.1 Autografts

7.1.2 Hamstrings

The hamstring graft is one of the most used graft types for ACL reconstruction. It can be prepped in different techniques, such as two, three, four, five, six, or eight stranded grafts. Hamstring grafts are often chosen for athletes, young, possibly still in the growing process, and active individuals who require a faster recovery to return to their normal activity levels because it is less invasive than other graft harvesting techniques. However, this graft is generally not recommended for high-level athletes, as other types of graft tend to offer better biomechanical strength for sports since athletes such as sprinters rely on their hamstring musculature. The hamstring graft has good biomechanical properties, with almost double load to failure compared to the native ACL, but it depends in the preparation and how often it was folded. (8)

Figure 2- MRI scan after HT graft reconstruction

Nowadays the reconstruction of the ACL by hamstring grafts is performed by using the minimally invasive or anteromedial approach also known as OLIBAS technique (13,14). Another option for the graft harvest is the posteromedial or minimally invasive approach(15). Next to the surgical approaches, the graft preparation is another point to consider since it makes the graft a versatile option and allows for easier and better individualization.

The surgery methods have some advantages and disadvantages. The most obvious advantage includes the ease of the harvest process, which is, in comparison to the BPTB graft, less invasive because it spares the patella. This furthermore decreases the chance of acquiring anterior knee pain, which is mostly associated with the extraction of the bone plug of the patella. Also, kneeling pain is lower in comparison to BPTB grafts. The harvest also lessens the chance of having a high donor site morbidity and it has almost comparable strength properties as the native ACL. (8,16)

Furthermore, the harvest is, by using the minimally invasive technique, cosmetically in favor, since the scar is smaller and at a less visible site in comparison to other graft harvesting techniques. The minimally invasive approach also allows faster graft harvesting since it is superficial and less complicated in the surgical process. Also, the passage through the drilling holes is easier than with graft types with bone plugs. (13,17)

One of the main advantages of the hamstring grafts is the individualization, allowing the surgeon to customize the graft according to the needs of the patient and tailoring it to the patient’s anatomy. The hamstring graft also doesn’t compromise the functionality of the extensor musculature. (8,18)

Figure 3- Harvested HT graft

Figure 5- Folded HT graft

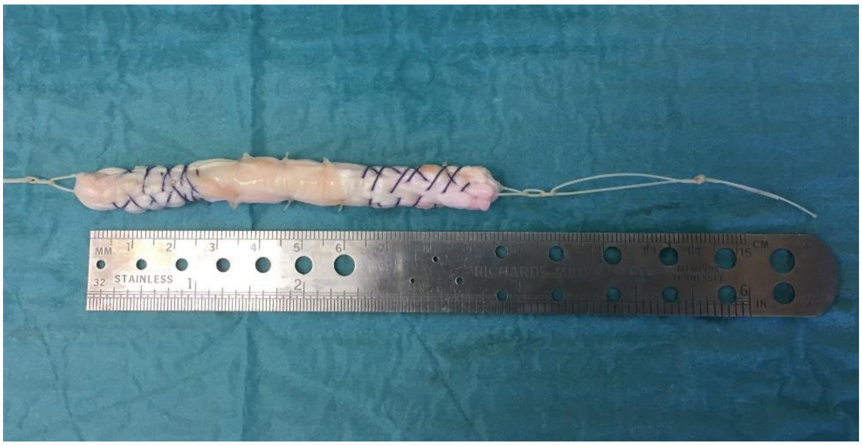

Figure 4- Prepared HT graft

Next to the advantages of the hamstring graft, the surgery methods also have their downsides. One of the disadvantages is the more complicated graft fixation, which is due to the lack of the bone plug that other graft types offer. The hamstring graft also takes a longer time to ligamentize, leading to a prolonged healing time (19). The healing time or incorporation time for the hamstring graft is approximately 12 weeks, which is around two to four weeks longer than with BPTB grafts. Like the other grafts, the hamstring graft also has the risk of producing hematomas and an increased risk of infection. (8,18) Furthermore, the graft itself to prepare is more complex and the size can be hard to evaluate due to anatomical variations in patients. This issue of determining the proper size leaves the risk of choosing not the appropriate size, which may cause tunnel widening due to the windshield wiper effect, micromotion, bone resorption, swelling of the graft. The phenomena of tunnel widening is also occurring more frequently than with BPTB grafts. (18)

Another issue with soft tissue grafts is laxity. The laxity is greater with hamstring grafts than with quadriceps tendon grafts, seen in a greater pivot shift laxity. The laxity is suspected to come overtime and is associated with the femoral suspensory fixation. The laxity also can be associated with the size of the graft, which can be avoided by using a wider graft with more strands. (16,19,20)

Besides the complex preparation, muscles damage may decrease the strength of the muscles involved in flexion and internal rotation. The loss of strength can be seen especially in women with approximately 13%. The damage of the muscles increases the risk of muscle tears at the harvest site. (16,18,21)

Next to the advantage of being cosmetically good, the site of extraction increases the risk of injuring the saphenous nerve. The anteromedial approach is associated with a higher risk of infrapatellar and saphenous nerve injury (17). Furthermore, the revision rate is higher in comparison to the BPTB graft. The revision rate of the hamstring graft is around 17%. (8,18,22)

7.1.3 Quadriceps tendon

The quadriceps tendon is, next to the already beforementioned graft types, another option for the ACL reconstruction surgery. This type of graft can be used in various preparation techniques. The quadriceps tendon can be either used as a bone tendon graft or as a full soft tissue graft. This makes the quadriceps tendon a versatile graft option. The quadriceps tendon is mostly used in patients who are young and skeletally mature or immature where the graft is then taken just as a soft tissue graft.

Moreover, this graft is a good option for reconstruction when the native ACL has a large diameter (>16mm). The size and mechanical properties are also relatively comparable to the native ACL (2100 N) and the graft with a load to failure of 2352 N. The quadriceps tendon is also, besides using it for the young patients, used for athletes who are dependent on their hamstring musculature such as sprinters. It is also in favor for patients whose activities involve kneeling. (8,18)

The quadriceps tendon graft has several surgical approaches. First there is the difference in the incision, whether it is an open approach or a minimally invasive. Next, the graft itself can be a superficial tendon, or a full thickness graft, and it can be combined with a bone plug or just used as a soft tissue graft.

All the procedures, whether they are minimally invasive, open approach, soft tissue or with a bone plug, have their risks, advantages and disadvantages. The minimally invasive harvest methods are in general, with its incision size less invasive than an open approach, which leads to less wound area and a better cosmetic result in terms of scar size and the risk of wound healing impairments can be reduced by a smaller length of the incision. (23–26)

The quadriceps tendon graft has the advantage with less donor site morbidity, such as anterior knee pain and the potential risk of fracturing the patella. But this is only the case if the graft is a full soft tissue graft(12). While the quadriceps tendon graft can be also harvested with the bone plug, this increases again the risk of the patella fracture since it is retrieved from the superior pole. Compared to the BPTB graft, the anterior knee pain is less in the quadriceps tendon graft since the bone plug of the BPTB is taken from the distal pole of the patella. (26–28)

Furthermore, the risk of injuring the saphenous nerve is reduced in the quadriceps tendon graft compared to the bone patella tendon bone graft. Next to the reduced risk of injuring the nerves around the knee, the chance of shortening of the patella ligament is less since the surgical field is around the quadriceps tendon. (25,27–29)

Another advantage is the site of harvest. The quadriceps tendon can be either harvested as full thickness or superficial graft, providing versatility and options for individualization(27,29). Furthermore, since the QT graft preserves the hamstring functionality, it makes this graft type a good option for athletes who are dependent on their hamstring musculature. Also, mobilization can be faster with the quadriceps tendon graft with a bone plug since the process of healing within the tunnels is faster because bone-to-bone has a faster recovery time. The ligametization process of the hamstring grafts is around 12 weeks and in quadriceps grafts in 6-8 weeks, leading to a faster recovery time. (24,26,27,29,30)

Another advantage of the graft is the lower incidence of retears compared to other graft types and therefore a favorable option for revision surgery. The quadriceps tendon can also be used as an additional graft in case of multiple ligament injuries. (12,27,29)

Next to all advantages the surgical approaches have, the quadriceps tendon graft has also downsides. The graft with a bone plug can be a potential risk factor for a patella fracture (27,28). Also, the bone-to-bone healing can be impaired, leading to a decreased stability of the graft (26). Furthermore, the QT tendon has a failure rate of up to 4,1%(18).

Furthermore, there is an increased risk for intramuscular or myotendinous injuries, as well as intraarticular hematomas, resulting from joint opening. Another complication is the quadriceps muscle which is associated with atrophy postoperatively and, therefore musculature weakness and compromised proprioception. (12,24,26,27,31) Also, retraction of the femoris recuts muscle can be seen in some patients when the harvest extends beyond the transition area of the tendon into the muscle. Furthermore, there is a risk of a short graft depending on the anatomy of the patient and the surgeon’s expertise. (26)

In some operative approaches, there is an increased risk of wound healing and excessive scarring, which is at increased risk in open approaches since the incision area is larger than with minimally invasive approaches. (12)

Next to all the patients associated risks and downsides to the graft, the surgical risks include the technical challenging harvest method. Not all surgeons learn this approach since it is new and not as often used as the other approaches. (26,29)

7.1.4 BPTB patellar tendon

The patellar tendon is one of the most used graft sites for the anterior cruciate ligament reconstruction. This graft is usually chosen for athletes since this graft has low recurrence rates and a fast return to sports. Furthermore, patients who are young and skeletal mature, workers in mechanical and physically demanding jobs and athletes who are performing hamstring dependent sports such as hurdles, sprinters and gymnasts are good candidates for the BPTB graft. Furthermore, the BPTB graft has a high load to failure and combined with the bone-to-bone healing and fast recovery, its biomechanical properties are favorable compared to the native ACL. (8)

Figure 6- Prepared BPTB graft

The two-incision technique allows for the tibial tunnel to be drilled through the same incision used for graft harvesting(32). This type of graft has the fastest healing and incorporation time which is approximately around 6 weeks (8).

Reconstruction using the BPTB (bone-patellar tendon-bone) graft is associated with several disadvantages, including the risk of revision surgery and other postoperative complications. The revision rate for BPTB grafts within a 15-years is approximately 8%, which is lower compared to other graft types. Quadriceps tendon and hamstring tendon grafts have shown higher revision rates compared to BPTB. (33–35)

Disadvantages of the BPTB graft include the potential for graft-tunnel mismatch. This is caused because the BPTB graft has a fixed length, leading to complications when the tunnel length is not precisely measured and adjusted (36). Another drawback is the higher incidence of anterior knee pain, which is problematic for patients who need to perform frequent kneeling as part of their daily activities or work (32).

Approximately 10% of patients fail to regain their pre-injury level of activity. Lachman test outcomes range between 4.6% and 25% positive for instability in patients with BPTB grafts, while the pivot shift test shows a positive result in 6.5% to 19% of cases. Furthermore, increased postoperative knee laxity has been reported in 22% of cases, with BPTB graft recipients experiencing greater feeling of instability compared to those treated with hamstring tendon grafts. (33,37)

Anterior knee pain is another reported donor site morbidity associated with the use of BPTB grafts. Within the first two years approximately 52% of patients report experiencing anterior knee pain. Next to AKP, patellofemoral osteoarthritis can occur due to the harvest site (38). By performing a minimally invasive or double-incision approach, this reduces the risk of damaging the infrapatellar branch of the saphenous nerve, while also minimizing soft tissue injury during surgery (32,39,40). Additionally, the use of specialized graft harvesting instruments facilitates a more minimally invasive procedure, further reducing trauma to the surrounding tissues (41).

Another possible, but rare donor site morbidity is patellar fracture, a complication linked to the harvesting technique that involves sawing into the patella. Patellar fractures are relatively rare, with an incidence ranging from 0% to 1.3% (8,42).

Figure 7- Patellar fracture after ACL reconstruction with BPTB graft

7.2 Fixation methods:

During ACL reconstruction, the graft must be fixed into the tunnels in order to provide stability and biomechanical functionality. There are several methods including interference screw fixation, which can be done by placing the screw through a guide wire and then by compression held place. The screw material can be either metal, plastic or an absorbable material. One major downside of the interference screw is the material removal, in case of non-absorbable material, and MRI artefacts due to the interference of the material and the imagine method (43). Bioabsorbable material has shown to increase the risk for tissue reaction and osteolysis (43).

Another fixation method is the suspensory fixation, where the graft is held in place with either a cortical button, staples, a screw or a washer. This is commonly used in soft tissue grafts. But in this method risks such as tunnel widening and increased motion in the tunnel of the graft, due to the windshield wiper effect, can potentially occur, which influences the integration process negatively (43,44). Although the advantages of the suspensory fixation includes that it is less invasive and there is an increase in tension at the bone and graft site (44). Another fixation of the graft can be performed by placing a suture through the graft and anchor the sutures with a screw. This method puts a constant tension on the graft during movement patterns and therefore often used as a backup fixation in certain cases, even though that this method has a risk of the pullout of the anchorage (45).

The fixation methods generally cannot be defined into a method that is better than another. The reviews and clinical studies are limited and vary in their findings which make a definite superior method difficult to define.

7.3 Synthetic grafts

Synthetic grafts have gained popularity since the 80s and 90s. During this period, synthetic grafts were developed because autologous and allografts have their disadvantages, which made the innovation of synthetic grafts, with different kinds of materials, an approach of interest. This could decrease the donor site morbidities, the time of rehabilitation could be shortened and the surgical methods eased. There have been different approaches such as carbon fiber, Gore-Tex, PTFE, Dacron, Leeds- Kaio and the newest LARS approach. (47–49)

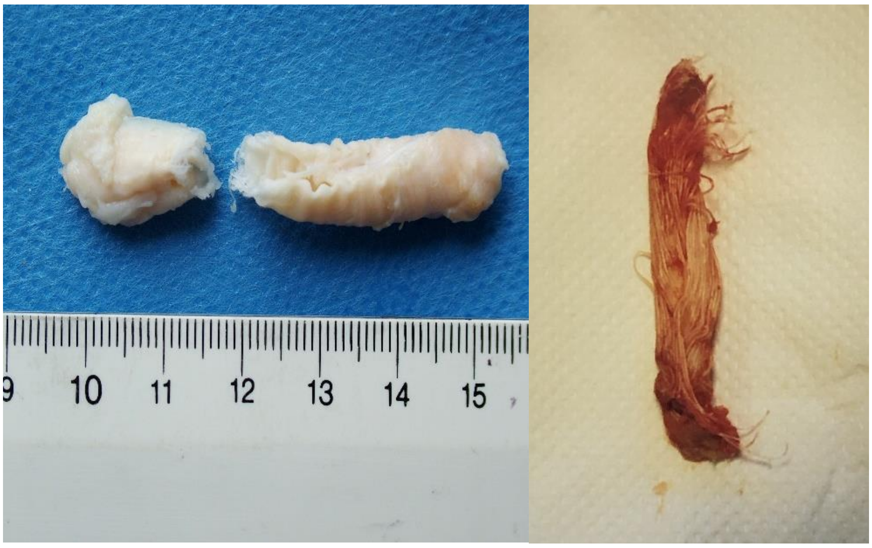

Figure 8- Synthetic graft failure

Carbon fiber has been one of the first modern attempts, trying to create a synthetic graft option in the early 80s. Beforehand, there have been several approaches with Teflon, carbon and polyflex, which mostly resulted in high ruptures rates and inflammation of the knee, leading to the approach of carbon fiber developed by Jenkins et al (50). They initiated the use of carbon fiber in tendon replacement and then extended the approach on to the ACL reconstruction. Later on, Dandy et al. (51) were using this approach, but later retrieved from using carbon fibers since there were too many post-surgical complications, such as pain, effusion, synovial changes, osteoarthritis halo sclerosis, particles of carbon fiber scattered in the joint cavity, and insufficient adherence from the graft in the bone. (52–55) These complications were linked to the carbon fiber material and its performance within the joint. It seems that the fibers were not compatible with the loading forces, which the ACL must undergo, leading to the fragmentation of the graft over time. The carbon fiber is not used anymore due to the poor outcomes. The complications are too abundant, leaving the carbon fiber a synthetic graft where research has not been implemented any longer. (53,54,56,57)

Another option, to the carbon fiber, is the Gore-Tex made from polytetrafluorethylene, also called PTFE, which should be used as a reservoir if autografts have failed in patients. The Gore-Tex graft had one advantage to the other grafts, which was the ultimate tensile strength of 5300N, whereas the native ACL lays around 1700N. Several studies showed that the Gore-Tex graft had complications specifically in the breakage and fragmentation of the graft after a certain period of time. (58–63) Furthermore, leading to knee instability, synovitis and tunnel impairment(58,61). These complications lead to the abandoning of the graft since it was not a suitable option for ACL reconstruction.

The Dacron graft was also developed in the late 80s, and it was made out of polyester, with a width of 8mm, and a core made from four tapes, which were woven into each other and surrounded with the same woven pattern but not as tightly (64). The Dacron graft was found to have complications like the Gore-Tex. Some studies have shown that the Dacron graft had troubles in rupture rates, ranging from 30%-60%, graft failure, laxity and degenerative osteoarthritis. These outcomes and complications made the Dacron graft an unsuitable graft and therefore abandoned. (65–68)

Other synthetic grafts such as Leeds-Kaio, Kennedy LAD and polyester were also used and abandoned due to the high rates of complications. (48,64)

The newest model is the Ligament Advanced Reinforcement system, short LARS. This was developed in the late 90s. The grafts' structure composition is made of PET fibers with two zones of which one should enhance the process of integrating in the tissue surrounding it. Some studies state that the graft allows the patients to regain strength and early rehabilitation due to the absence of autologous graft harvest surgery. The graft is favorable for joint stability and allowing patients to return to sports faster, which makes the graft suitable for some patient groups (less active patients).(69–73) The overall complications are synovitis, failure rate, graft laxity, but in a reduced percentage compared to other synthetical grafts(74–76). The studies are controversial in their opinions on this type of graft because the outcomes are relatively positive, whereas with other synthetic grafts, the complication rate was too high in order to use the grafts in patients (77,78). This makes the graft, possibly a graft type where the surgeon must decide whether the patient is a good candidate for this system.

Nowadays, approaches have been established to enhance integration of synthetic materials into bone and therefore improve outcomes and re-rupture rates of synthetic grafts. This can be done by using biological coatings that could enhance osseointegration. The integration of synthetic grafts is believed to be poor since the material has hydrophobic properties and fibrovascular scar tissue, coming from surgery, leading to disturbed integration. (64)

Effective coatings include for example Bioglass and Hydroxyapatite, which should enhance bone growth, Silk fibroin should increase the process of ligamentization, Graphene coatings are supposed to also enhance the integration process of the graft, Polydopamine supposed to enhance cell attachment, proliferation, and osteogenic differentiation. These materials though have their downsides, including immunological processes and reduced mechanical properties, leaving these materials a questionable alternative. Therefore, further research is needed in order to define potential approaches for reconstruction and enhancement of the process of ligamentization.(64)

7.4 Allografts

Allografts are another option for the reconstruction of the anterior cruciate ligament. The allografts are especially used if there is a need for a reduced donor site morbidity, which is often the case for older patients above 40 years of age or children. Furthermore, patients with either multiligamental knee injury or if a patient already received an autologous graft reconstruction and therefore no possible donor site, allografts can be a viable option. (8)

The allografts include a broad number of options. There are soft tissue options and bone tendon bone grafts. The BPTB is the only option, which provides two bone healing sites, whereas the others such as achilles and quadriceps tendon only have one. Other options include tibialis anterior and posterior, hamstrings, peroneal and fascia lata as soft tissue options. The graft must be specially ordered for each patient since the anatomy varies among age and gender leaving the allografts very customizable by searching for a donor graft suitable for the patients' needs. (79–82)

The allografts have several advantages such as absence of size limitations leaving the allografts a viable option in case of multiligamental injuries, variety of grafts, a reduced surgical time, and absence of donor site morbidity(83). There are not only positives, disadvantages include higher costs due to the sterilization and storage (84), higher failure rates, disease transmission, longer healing time and reduced return to sports.(8)

The ligamentization process is also, in regards of the allograft, an important step of the healing process. The healing process or the ligamentization process with allografts, is according to Condello et al. (77) slower but the process is the same as with autografts. There are three steps which are considered the standard. First, there is the "an early and acute inflammatory process with ischemic necrosis and no detectable revascularization; then, cell recruitment and chronic inflammation with revascularization, proliferation and collagen remodeling; and finally, a ligamentization phase" (85). The steps must be differentiated between soft tissue healing and bone to bone healing. The bone-to-bone healing takes around 6 weeks and soft tissue to bone around 8 to 12 weeks (82). Another consideration, highlighted by Iosifidis et al.(86) in their systematic review, is the potential immune response between allograft donor and recipients, mediated by the MHC class I and II. These reactions are still not fully understood, leaving the clinical relevance not fully cleared and a possible field of interest in research.

Another important topic to consider, in allografts, is disease transmission. Diseases of concern are HIV, hepatitis b and c human T-cell leukemia virus, syphilis aerobic and anerobic bacteria. There are special testing methods performed, including ELISA and PCR, in order to eliminate the chance of transmitting a disease through the allograft. (80–82,86)

To prevent immune reactions, disease transmission and also to make the graft long lasting, the grafts can be sterilized and prepared, preserved in different kinds of mechanisms. Firstly, the donors' age ranges from 15-50 years and the history of diseases are carefully taken for prevention. The next important steps include the sterilization and storage of the allografts. The sterilization process is done in an aseptic environment. The sterilization is performed to prevent disease transmission but preserving the materials structure and functionality. This can be done by several processes. Firstly, gamma irradiation, with either low dose or high dose irradiation can be used. The high dose irradiation is considered to affect the mechanical structures of the soft tissue immensely(80), whereas low irradiation is considered relatively safe but still having the potential of altering the structure of the graft(81,85). On the other hand, the allografts can also be sterilized without irradiation. Tisherman et al.(81) found in their systematic review that the nonirradiated grafts have a higher risk of failure load and higher stiffness but a decreased risk of graft failure. Liu et al. (87) also support the non-irradiated grafts because the biomechanical properties of the graft are not altered by radiation. This systematic review showed that the nonirradiated grafts had a decreased risk of failure and better functional scores (87).

Other option are chemical methods such as BioCleanse and AlloTrue. In a systemic review of Hulet et al. this method has shown to have a negative impact on the mechanical properties and an increased risk of graft failure. (82,85)

Preserving the allografts can be done in three different methods, consisting of deep fresh frozen, freeze-drying and cryopreservation. Tishermann et al. (81) found in their review that the BPTB and tibialis posterior freezed, from 30 days to 9 months at -80°C, didn't affect mechanical properties of these grafts, but the achilles tendon to be affected with a decreased max. load. Iosofidis et al. (86) have described that the deep-frozen method has no major impact on the biomechanical properties and a positive impact on donor and recipient immune reaction. Furthermore, the freeze-drying method is also widely used with similar positive results on the graft and recipient reaction.

Within the storage and preservation method the studies have shown that the nonirradiated fresh frozen method is the best option for as far as literature can indicate (88).

Tabbaa et al. (89) found in their systematic review and meta-analysis that the total failure rate of allografts was around 11% and the graft rupture rate from bone to soft tissue 6% and soft tissue 13% in total. The bone-to-bone grafts seem to have a better incorporation and healing process, leaving that graft type a possible better option than a full soft tissue graft. The study has its limitations since literature is scarce and more literature is needed for the outcomes of allografts.

Another systematic review has studied the revision and failure rates of allografts which were done by Engler et al. (90) In this review the authors tried to define differences within the allograft types in terms of revision and trying to include factors such as preservation, sterilization and the type of allograft used. They found out that there were no significant differences between the allograft types in revision rates. Furthermore, they couldn't define a difference in revision rate between the graft types whether a full soft tissue or bone soft tissue grafts. Lastly, they were not able to find a significant difference between low or high dose irradiated grafts.

Other studies in general were not able to find major differences in allografts (nonirradiated) and autografts in terms of failure rates, patient outcomes and complications (91–93). But Irradiated grafts were less favorable in its outcomes (94).

The studies are generally limited due to a shortage of studies comparing the graft types with each other and differentiating the sterilization and preservation processes. Also, the variety in combinations of graft types and how each one has been processed and furthermore being influenced by factors such as gender, other ligamental injuries, previous ACL reconstructions, body weight and patient compliance for rehabilitation, show the need for large randomized-controlled studies. This makes it difficult to say which graft is the best option for an individual patient.

7.5 Comparison of graft choices

This section will analyze the beforementioned facts and graft types such as BPTB, quadriceps, hamstring tendon autografts, allografts and synthetic grafts in their results and patient specific outcomes.

Table 1- Comparison of grafts

Graft Type	Advantages	Disadvantages	Healing Time	Failure Rate	Who
BPTB Autograft	Strong fixation, lower revision rates, faster return to sports	Short graft length, AKP, patellar fractures, nerve injuries, osteoarthritis,	~6 weeks	~6%	Athletes, young active individuals

		tendon rupture, tendonitis			
Hamstring	Little AKP, low donor site morbidity, graft size customizable, extensor muscle preservation, minimally invasive approach-> less operative time and less scar	Long ligamentization process, hematoma, tunnel widening, windshield wiper effect, laxity, more complex preparation	~8-12 weeks	~17%	Athletes not dependent on their HS, general population, immature or mature patients in their growth
Quadriceps	High variability, open and minimally invasive approaches, soft tissue graft and bone plug, decreased nerve injury risk, AKP less, lower donor site morbidity	Patella fracture (bone plug), quadriceps musculature atrophy and weakness, less surgeons know the techniques	~6-8 weeks	~ 4,1%	Young active, patients dependent on their hamstring musculature, kneeling jobs, skeletally mature or immature
Allograft	Shorter surgical time, no donor site morbidity, less size limitations, variety of options	Higher costs, higher failure rates, longer incorporation time, disease transmission, little research done	~6-8 weeks with bone plug, ~12 weeks with soft tissue grafts	Varies	Older population, less active in sports, multiligamental knee injury

Synthetic	Possible easier surgical approaches, no donor site morbidity, shorter rehabilitation time, variety of options if sufficient	In the past: fiber fragments in joint space, osteoarthritis, effusion, synovial changes, laxity, long incorporation time	Insufficient data	High	Too little knowledge and studies about who would profit.

7.5.1 Biomechanical strength

Biomechanical strength in ACL reconstruction is an important factor to face. The ACL withstands high pressure and forces to resist, where the transplanted graft needs comparable properties. Since the BPTB has two bone to bone healing points, this graft has seemingly the better strength compared to soft tissue allografts or autografts, such as full soft tissue QT or HT grafts. The soft tissue grafts have good strength, but a slower incorporating time whereas the QT graft fits in the middle, with one side with a bone plug and the other site soft tissue, in terms of strength and incorporation time. Synthetic grafts have a high tensile strength compared to the native graft, which was already mentioned before but since it degrades over time, the strength decreases and therefore produces a higher risk for graft failure and revision.

7.5.2 Surgical complexity

Some grafts have the variability to be harvested either in an open approach or minimally invasive, which makes the complexity very variable. The least complex approaches are synthetic and allografts since there is no need to harvest an autograft prior to the insertion of the graft. The BPTB or QT grafts have more complex approaches because there is the need to harvest a bone plug. This makes the whole process more complex and longer since the autografts go a step further than the allografts or synthetic grafts. Furthermore, HT grafts are easier to harvest with several options in techniques, including open and minimally invasive options.

7.5.3 Donor site morbidity and postoperative complications

After surgical interventions patients can suffer from donor site morbidity, which is associated with graft harvest in case of ACL reconstruction. It is important to decrease the risks in order to have better results with the rehabilitation process. Therefore, patients undergoing BPTB graft harvest, are associated with an increased risk of AKP and patella fractures. Next to the BPTB graft, patients with QT grafts can also suffer from AKP but the risk is lower than in BPTB since the site of the harvest is not the distal patellar pole but the proximal. QT graft patients though have a higher risk of dealing with quadriceps muscle weakness and atrophy, in some rare cases even retraction of the rectus medialis muscle. The muscle weakness is also associated with HT grafts, where the grafts are taken from the semitendinosus and gracilis most often. This makes the HT grafts compared to the other autografts in favor of knee pain because there is no direct harvest connected to the patella. Synthetic grafts, on the other hand, have no donor site morbidity issues since there is no graft harvest. But the risk for synovitis due to the foreign body reaction, graft failure and prolonged incorporation times can occur, which is not the case of autografts. Allografts, on the other hand, also don't have specifically an increased risk of donor site morbidity but they carry risks of transmitting diseases and rejection reaction.

7.5.4 Tunnel widening and graft laxity

Hamstring grafts are most associated with an increased risk for tunnel widening due to the longer ligamentization process and fixation methods. This, furthermore, leads to an increased risk of laxity. Allografts without bone plug fixation are also commonly at risk of laxity. This risk compared to HT grafts is less in BPTB and QT grafts since they have bone-to-bone healing, which makes the ligamentization process faster and less likely to have a windshield wiper effect on the tunnel. Basically, decreasing the risk for laxity further. Synthetic grafts also have an increased risk for laxity and widening of the tunnel due to the poor incorporation process. Laxity and tunnel widening can influence patients' long-term outcomes since laxity has effects on the joints 'stability and therefore further complications.

7.5.5 Healing and incorporation time

As already mentioned, Bone-to-bone healing is the fastest in healing time with approximately 6 weeks. This makes the BPTB and quadriceps the fastest in terms of incorporation. HT grafts and allografts (soft tissue) take longer time, around 8-12 weeks, since the incorporation and ligamentization process takes longer due to the lack of bone-to-bone healing. Furthermore, synthetic grafts are associated with major issues in the integrating processes due to the foreign body response. There are trials on biological augmentation processes, which are supposed to improve the incorporation process(64).

7.5.6 Immune response and disease transmission risk

This section is specifically an issue of allografts and synthetic grafts. Allografts have an increased risk of disease transmission, even though there are processes of sterilization and testing that should limit this risk. Furthermore, synthetic grafts are associated with an increased immune response and therefore with altered joint properties, leading to synovitis and foreign body reaction.

7.5.7 Failure and re-rupture rate

The grafts have, depending on their fixation method, and their own properties, different rates of rupturing or failure. BPTB grafts have a failure rate of approximately 8%. Quadricep grafts have a rate of up to 4,1%, whereas hamstring tendon grafts have the highest of up to 17%. Due to the different types of grafts, the failure rate can vary highly. Therefore, the soft tissue grafts have an increased failure rate since their integration time and ligamentization process is slower compared to bone plug grafts. This also applies to allografts. They have longer integration processes and leave an increased risk of failure. Synthetic grafts also had poor results in failure rates.

7.5.8 Long term outcome and return to sport

BPTB and quadriceps have the highest return to sport because the graft type allows a quick and fast rehabilitation process. Hamstring and other soft tissue grafts have a good return to sports, but this type of graft has the potential risk for laxity, leaving the rehabilitation process still fast but slower compared to other grafts. This is also associated with the longer incorporation time. The longer incorporation time is also a concern for the return to sports of allografts. This makes the return to sports, compared to the other graft types, the least favorable.

7.5.9 Osteoarthritis

Osteoarthritis doesn’t only occur due to age. Surgeries, especially ACL reconstruction, can increase the risk of OA in patients. This is commonly associated with the harvest of a bone plug, specifically patellofemoral osteoarthritis. On the other hand, soft tissue grafts and allografts without bone plug can increase the risk of osteoarthritis because they can have a certain amount of laxity accompanied with joint instability, which, over time, can accelerate the joint degeneration. The joint degeneration is also associated with synthetic grafts due to the fragmentation of the graft.

7.5.10 Patient specific graft decision

Each graft can be specifically used for specific patient groups. Therefore, it is important to choose the correct graft for each patient and their specific needs. Patients who perform pivoting and cutting sports should be considered for BPTB and quadriceps tendon grafts with bone plug. Patients who have kneeling jobs or perform sports, who need an intact extensor musculature, should be considered for HT graft or allografts. If the patient is older or has poor autograft material, allografts can be used. Furthermore, allografts and synthetic grafts can be used in patients with multiligamental knee injury or if there have been several revision surgeries.

7.6 Extraarticular stabilization of the knee

Anterior cruciate ligament reconstruction is commonly performed, however certain cases with persistent laxity and rotational instability or during revision surgery with a positive pivot test, extraarticular stabilization surgeries could be considered.

The indications for the surgical approach include patients who are in need of a revision of ACL reconstruction, a high grade laxity with rotation, patients with a general ligamentous laxity, genu recurvatum of >10° and young patients and athletes who perform sports with pivot motions (95). Furthermore patients, who are at high risk, should be provided with LET such as young athletes with a HS graft(96).

7.6.1 Surgical techniques:

7.6.1.1 Lamaire:

In this procedure the iliotibial band, measuring 18cm x 1.5cm, is attached to the Gerdy's tubercle and attached to the femur side above the lateral epicondyle. The graft is passed under the LCL. A newer approach is the modified Lamaire, where the band is only 100x15mm and the strip is fixated with an interference screw. (97,98)

7.6.1.2 MacIntosh:

In this procedure a 15x150mm strip of the ITB is attached to the femoral epicondyle, where a subperiosteal tunnel is formed directly at the insertion point of the FCL. The band is then passed underneath the FCL, and a second tunnel is placed at the distal insertion of the lateral intermuscular septum. In earlier days the band was attached with sutures at the periosteum and nowadays with an interference screw. (97,98)

7.6.1.3 Ellison:

The procedure is done by creating a band with a width of 15 mm of the ITB by detaching it with an osteotomy at Gerdy's tubercle. The strip is then passed underneath the LCL and reattached to Gerdy's tubercle. (97,98)

7.6.1.3 Loose:

A 12–14 cm by 2.5 cm strip of the ITB is harvested. A 9 mm tunnel is created from the anterior-inferior aspect of the femoral attachment of the FCL. The graft is passed through the tunnel and secured to the periosteum. It is then pulled back through the lateral gastrocnemius tendon, the capsule and underneath the FCL. The ITB graft is reattached to Gerdy's tubercle. (97,98)

7.6.1.4 Arnold-Coker:

In this procedure a 15-18cmx2cm strip of the ITB is taken and the attachment at the distal end is preserved. The graft is then passed underneath the FCL and back to the Gerdys tubercle. The strip is then sutured to the FCL and at the tibial portion with a staple. (97,98)

7.6.1.5 Modified Andrews:

This technique includes a graft size of 20mm of the ITB. The graft is fixed at the Krackow point which is located distally of the intermuscular septum insertion. The band is then fixed with an interference screw. (97,98)

Generally, it can be said that the current literature recommends the modified Lamaire approach. This can be alternatively replaced by the Ellison or the anterolateral ligament reconstructions (95,99). Furthermore, ACL reconstruction with Cocker can also be an alternative to Lamaire(100). Current systematic reviews show that the patients have an improved stability up to 60%, anterolateral and anteroposterior, which is tested by the pivot shift test, Lachman and KT-1000 arthrometer. Also, the graft failure rate could be decreased by implementing LET into revision surgeries (101–104). A systemic review, by Rezansoff et al., showed no significant difference between the return to sports in patients either receiving a reconstruction with or without LET, thus a decrease in re-rupturing(105,106).

In a multicenter, prospective, randomized clinical trial by Getgood et al. (107), they were able to prove a significant difference in the reduction of graft rupture and laxity in patients with a single bundle HS autograft in young patients. In this study one limitation seems to be apparent by using several different surgical techniques with different fixation methods, which can limit the outcomes in the sense of every method has its specific risks and complications, making the analysis. These results were, furthermore, proven by several systematic reviews and studies, by searching for the complications or reinjury of the ACL in context with LET or ALL reconstruction(1,108).

7.7 Graft augmentation

In ACL reconstruction graft augmentation is an approach, which is used to reinforce a reconstructed ligament by adding various biological or synthetic materials. This approach is mostly chosen in patients who are at high risk of revision surgery or graft failure. Basically, there are several approaches, including the augmentation of autografts with biological solutions, such as platelet rich plasma or stem cells, furthermore the ACL can be stabilized with an internal brace, dynamic intraligamentary stabilization or BEAR implant.

7.7.1 Internal brace or suture tape augmentation:

One of the main augmentation types is the internal brace. The internal brace is an approach where the ligament is stabilized by a high strength suture tape. It can be used either when the ACL is primarily repaired or during reconstruction, acting as a stabilizing agent, which should prevent the risk of stress on the ACL during early healing time. (109)

Conde et al. (110) conducted a systematic review and meta-analysis on the comparison between primary repair and ACL reconstruction with the internal bracing as an additive. Therefore, they were able to define a significant difference in the failure rate between IB and the reconstruction. The Internal bracing sole had a higher failure rate than the ACL reconstruction combined with the IB. But compared to the reconstruction, the sole IB had less hamstring strength loss than the reconstruction with a hamstring autograft. The analysis has its limitations due to the literature being scarce, leaving some results unanswered and questionable.

Next to the comparison, between either the reconstruction with or without IB Maginnis et al. (111) conducted a systematic review about the difference between grafts themselves. They were able to find no proper disadvantage between the grafts in combination with internal bracing. However, due to the limited data, the systematic review compared animal and biomechanical studies with human studies. Therefore, the comparison is not sufficient in terms of the style of the studies included and also sample sizing was, in some cases, limited. There is a need for further randomized controlled trials to be able to put these findings into clinical significance. This is also a result that Dhillon et al. were able to state in their systematic review which leaves the internal bracing a topic where further research should be done(109).

7.7.2 Biological augmentation methods:

Another approach is the enrichment of the graft with bone marrow aspiration concentrate, which can be combined with platelet rich plasma. This is supposed to enhance the graft in steps of incorporation into the bone.

A fairly new approach is the BioBrace which is a biocomposite scaffold, which was produced to enhance graft healing and provide mechanical strength(112). There is no literature provided Pubmed, besides some surgical notes that don´t provide any relevant results.

Lin et al. (113) conducted a randomized prospective double blinded study in order to define if there is a difference in healing and incorporation between PRP, PRP and BMAC and ACL reconstruction alone. They were able to find differences between the groups where the biologically enriched groups had better incorporation, healing and clinical function. These findings must be carefully analyzed since the subject group was small. So the findings are limited, and further studies must be conducted in order to find significant differences. The incorporation and enhanced graft recovery was also analyzed by Park et al. (114) in their systematic review. This review also states that the results cannot be seen as significant since literature is limited, but the results on graft recovery seem to be promising.

Delcogliano et al. performed a scoping review on PRP augmentation. They were able to state that the literature is too scattered in order to define whether the PRP augmentation sole is sufficient and improves clinical outcomes(115).

Another approach is the BEAR, bridge-enhanced ACL restoration, implant. The bridge enhanced ACL restoration implant is based on collagen and is infused with blood from the patient in order to function as a bridge between the two ACL stumps and therefore holding the two stumps together in order for them to heal.

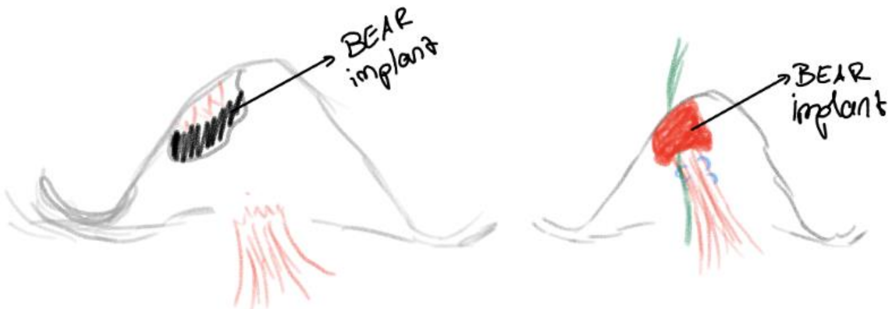

Figure 9- BEAR implant

There is one cohort study based on 2 year results of the restoration with the BEAR implant by Murray et al. (116). They used a small sample size and compared the functional outcomes between patients receiving hamstring autograft reconstruction and another group with only the BEAR implant. They were able to find no major differences in clinical function and patient reported outcomes between the autograft and BEAR implant. These findings were also supported by another retrospective cohort study (117), leaving the BEAR implant a possible and new option in ACL repair but more studies are needed.

7.7.3 **Dynamic intraligamentary stabilization:**

Dynamic intraligamentary stabilization is used as a primary repair instead of ACL reconstruction surgery. This is used to enhance the healing of the native ACL and preserve the biomechanical properties of the knee joint to prevent further injuries. The approach includes a Ligamys implant, which is placed into the ACL by pulling sutures through the ruptured ACL and fixate them with a dynamic screw. The DIS should be placed within the first days post injury to stabilize the joint during movement. (118)

Complications of this approach include a decrease in the range of motion and therefore higher revision rates than with the ACL reconstruction(119). Next to the decreased ROM, instability and revision due to failure rates are not favorable for this approach. Generally, DIS seems to have favorable outcomes especially for patients with lower activity levels and of older age. (120)

7.8 All inside technique

The all inside technique was developed in 1997. Therefore, the approach is minimally invasive and differs from the "traditional" ACL reconstruction. Usually in the traditional ACL reconstruction the femoral and tibial tunnels are full length tunnels, whereas in the all-inside technique closed sockets are used. In all-inside technique, the fixation is done by adjustable loop suspensory fixation. The tunnels are placed by using retrograde reamer devices. (121)

Advantages of this technique include firstly that the approach can be done minimally invasive by using two arthroscopic portals. Secondly, the patients' anatomical properties can be utilized by placing the femoral socket as needed. The tibial tunnel placement can be again chosen where it is anatomically adequate, which reduces impingement during flexion. The closed sockets have the advantage of less postoperative pain due to the less invasive bone drilling and preserving the periosteum. (121,122) Disadvantages include that this approach is more complex, which must be learned. Furthermore, the costs of the surgery cost approximately 18% more than the traditional ACL reconstruction. This is caused by the equipment costs(123). Therefore, this approach should be chosen for cases where the patient benefits the most by utilizing the all-inside technique.

Also, the fixation method has its downsides, which can cause tunnel widening and therefore graft healing impairment. Generally, this approach doesn't have decreased clinical outcomes compared to the classic ACL reconstruction but further studies on long term outcomes are needed. (124,125)

7.9 Graft isometry

The point of isometry can be defined as where the ACL length changes the least during its motion. This is important for placement of the tunnels and the future graft, since wrong placement can cause an increased laxity, graft failure and joint instability during movement.

During movement the ACL fibers tighten and loosen dependent on the angle of the knee. During extension the anteromedial and posterolateral bundles are tensed, which changes when the knee joint goes into flexion. In this movement the posterolateral fibers become loose, and the anteromedial fibers tighten, which mimics a twisting motion of the ACL during flexion. The isometry is, therefore, dependent on the anteromedial fibers, which experience only minimal changes during movement(5).

The insertion point of the femur is approximately 18x11mm in size and located in the deep aspect of the intercondylar notch close to the edge of the chondral bone(126). The tibial insertion is placed at the anterior horn of the lateral meniscus. The tunnel placement, therefore, plays an important role in prevention of postoperative complications such as insufficient knee joint biomechanics, osteoarthritis, graft failure and impingement of the graft. The tunnel placement can be determined with different methods. Yin et al. (127) analyzed in their modeling analysis the usage of the quadrant method, which determines to position the femoral tunnel 28% parallel and 22% perpendicular to the Blumensaat line. The tunnel angles should be placed 40° to the femoral shaft in the sagittal plane, 33° in the transverse plane and 38° in the coronal plane in flexion. The outer opening should be located 2cm above the lateral aspect of the femoral epicondyle. This allows the tunnel placement at a high aspect of the anteromedial bundle footprint. The femoral tunnel should be located at the anatomical footprint of the original ACL, whereas the tibial placement is also positioned at the medial tibial plateau to ensure correct graft tension(127).

Anatomical reconstruction, where the graft is not isometrically reconstructed, seems to have no major differences in clinical and functional outcomes(128).

Generally, it is important to position the ACL graft according to the patients' anatomical landmarks and its therefore best isometric point and at the right angle in order to prevent complications such as impingement, laxity, graft failure and osteoarthritis.

7.10 Double bundle technique

The double bundle technique was developed to regain a better anatomical reconstruction of the ACL, which derives from the ACLs natural anatomy, consisting of two bundles (anteromedial- and posterolateral). In the past, the single bundle technique was mainly used to reconstruct the ACL with one bundle especially the anteromedial bundle or something in between, focusing on the reconstruction of translation and not rotation. Therefore, the double bundle approach was developed. (129)

The double bundle technique is performed by placing two tunnels per bone in order to be able to reconstruct the ACL with a posterolateral bundle and anteromedial bundle(130).

Teng et al. (131) created a novel approach for the double bundle reconstruction, where they tried to mimic the native ACLs anatomy. The technique is called the tendon groove technique, where they create a groove between the femoral tunnels on the joint space. This technique should improve the incorporation of the graft into the bone and prevent the tunnel widening. This technique needs to be further evaluated in clinical trials and studies in order to gain outcomes and its clinical importance. (131)

The double bundle technique is supposed to enhance graft stability and improve functional outcomes. Therefore, several systematic reviews and clinical studies have been conducted. One study by Lim et al. (132) analyzed the re-rupture frequency in double bundle compared with single bundle. They were able to define that the double bundle technique seems to have little impact on the re-rupture rates in young and active patients when a hamstring autograft has been used(132).

Another retrospective study has been conducted by Bitar et al. (129) which analyzed the medium- and long-term results in return to sports and re-rupture of patients undergoing double bundle and single bundle reconstruction. They were able to define a slight significant decrease in the re-rupture rates in patients treated with double bundle. Another study by Seppänen et al. (133) were not able to find a significant difference between the two methods in manner of developing osteoarthritis. These findings can also be supported by a systematic review conducted by Elsenosy et al. (134) which underlines the importance of the need for more controlled and randomized studies in order to find a significant difference and apply these techniques in clinical practice.

7.11 The golden standard of ACL surgery

This section will be about defining the golden standard of ACL surgery in the year 2025. Usually, the gold standard was since the 1990s BPTB graft due to its most favorable outcomes in terms of clinical outcomes, failure rate, biomechanical properties and long-term complications. The quadriceps tendon, though, has become a viable alternative to the BPTB graft. In this thesis the gold standard is shifting to the QT graft, with regards to the limited literature compared to BPTB study availability.

The quadriceps tendon has become more and more popular in the last decades. The graft type has gained popularity due to its comparable biomechanical properties with BPTB grafts. The quadriceps tendon has the advantage of a larger cross-sectional area, which increases durability and prevents laxity over time. Also, the load to failure of 2352 N is higher compared to the BPTB graft with 1784 N. Furthermore, the QT graft with a bone plug has a better integration process compared to full soft tissue grafts, which leads to less occurrence of tunnel widening. Also, the bone-to-bone healing makes the integration process faster with 8 weeks compared to HT (12 weeks) and comparable to BPTB (6-8 weeks). The knee stability is also comparable to the BPTB graft when the QT graft has a bone plug. Since graft elongation and laxity is less than with HT grafts, this makes the QT graft superior to HT grafts.

The QT graft also has less donor site morbidity compared to BPTB grafts. This makes the QT favourable. It has lower AKP since the plug is not taken from the distal patellar pole, which also makes it a better option for patients with kneeling activities in their job or sports. Besides patients with kneeling jobs, the QT graft is in favour for the general population. The graft can be used in still growing patients or those who are fully matured and generally those who are athletic and performing sports. The BPTB graft, for example shouldn't be used in young patients who are still growing. Furthermore, minimalizes the QT graft the risk of patellar fracture due to the area of bone plug harvest. Of course, there is still a risk of fracture but decreased compared to the BPTB graft.

Also, the harvest methods can vary immensely with the QT graft since there are several types of grafts with being either full thickness, only soft tissue or with a bone plug. This makes the QT graft more versatile than the BPTB and HT grafts. The graft can be adapted to the patients' needs, anatomical variations and also in cases of revision surgery.

The QT graft also preserves hamstring function and therefore a good flexion of the knee. This is important for athletes who depend on their hamstring musculature.

Concerns such as a more difficult surgical approach and surgical time due to the experience levels have to be addressed but with training and more studies and advance in the techniques, the QT graft is an option to consider learning. Since the QT graft is a newer graft type option there is less evidence and less studies have been conducted compared to the BPTB graft, since this graft (BPTB) is more frequently and longer in use. Evidence suggests that the QT graft is comparable or even better than the BPTB and HT grafts, which makes the QT a graft to consider as a new gold standard.

Other new approaches such as allografts, in cases where autografts are contraindicated or older patients who are less active, are a fairly good alternative to the autografts. On the other hand, approaches such as LARS, DIS or BEAR might be in combination with biological augmentation in cases where autografts are not an option, also alternative methods.

The Quadriceps tendon should be considered a new gold standard, because it has less donor site morbidity, compared to BPTB, it is superior to HT grafts in terms of clinical outcomes and has comparable outcomes to BPTB grafts, leaving this as a good option for the, typical, young and active, ACL reconstruction patient.

8. Conclusion and practical recommendations

All in all, must be said that the BPTB is still the most used graft, but the trend should go to patients specific graft choice, where the QT graft might be the better option in most cases since its decreased donor site morbidity and comparable outcomes to the BPTB, eventhough more research must be conducted on the long-term clinical and functional outcomes. BPTB might be in certain high performing athletes still the better option, but the QT graft, with its versatility, seems to be a better option for the general popularity. Hamstring tendon grafts are still a good alternative but with an increased risk for laxity and revision, this should be reserved for certain cases, where bone plugs might not be an option. The HT graft should be considered in patients with multiligamental injury or who are at risk of patellar issues. Furthermore, are in certain cases, allografts and augmentation alternative options but these should only be considered in certain patients with less active lifestyles and older age due to the risk of failure.

The research should also focus more on alternative options such as internal bracing and ligament augmentation in combination with biological material, to possibly find options, which could enhance ACL reconstruction and repair. As there is a variety of options and different surgical approaches, the surgeon must find the best option for the specific case and their individual needs. But considering the patients age and activity level, the QT graft seems to be the best option for the general popularity. Generally, it can be said that there is no universal gold standard for ACL reconstruction but rather a variety of options since each patient has their specific history of injury, anatomical properties and outcomes.

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