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INTEGRATED STUDY MASTER FINAL THESIS

PKR raiščių transplantatų raida

Evolution of ACL-ligament Grafts

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Abbreviations

ACL – anterior cruciate ligament

ACLR – anterior cruciate ligament reconstruction

AHA department – Department of Anatomy, Histology and Anthropology

AP - anteriorposterterior

BMI – body-mass-index

BPTB – bone-patellar tendon-bone graft

BTB – bone-to-bone graft

CLI – cruciate ligament injury

HT – hamstring tendon

LARS – ligament augmentation and reconstruction system

LFC – lateral femoral condyle

MRI – magnetic resonance imaging

PCL – posterior cruciate ligament

PKR - Priekinis Kryžminis Raištis

PM – posteriomedial

PROs– patient-reported outcomes

PROM / PROMs – patient-reported outcome measure(s)

QT – quadriceps tendon

RTS – return-to-sport

Abstract / Summary

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Evolution of ACL-ligament Grafts

Aim: To investigate and evaluate the current landscape of anterior cruciate ligament construction and grafts used and present an idea of a new type of "vascularized" anterior cruciate ligament graft.

Objective: Search the literature about the methods for anterior cruciate ligament reconstruction over the years and look for benefits with different methods, and compile them to easily refer to each to show the development that has been happening during the years, as well as provide information about our research on developing a new type of "vascularized" anterior cruciate ligament graft.

Methodology: This master's thesis is based on a narrative format and case presentation. Most of the articles are from the last ten years; however, some older publications were included if they seemed relevant and useful to the context and content of this thesis. An open literature search was conducted to gather supporting material and explore the current landscape of anterior cruciate ligament surgeries. Research on vascularized grafts was conducted hands-on using cadaveric materials.

Results: The field of anterior cruciate ligament reconstruction has advanced significantly in recent years, with many graft types. Our idea of a vascularized graft could be a viable alternative to current grafts. Further studies are needed to improve the surgical technique and to investigate tissue morbidity. The findings regarding the size of anatomical structures are the basis of a vascularized graft to succeed.

Santrauka / Apibendrinimas

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Darbo pavadinimas: PKR raiščių transplantatų raida

Darbo tipas: Aprašomasis darbas + atvejo pristatymas

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PKR raiščių transplantatų raida

Tikslas: ištirti ir įvertinti dabartinę priekinio kryžminio raiščio rekonstrukcijos ir naudojamų transplantatų padėtį bei pristatyti naujo tipo „vaskuliarizuoto“ Priekinis kryžminis raištis - transplantato koncepciją.

Užduotis: Ieškoti literatūros apie priekinis kryžminis raištis rekonstrukcijos metodus per pastaruosius metus, ieškoti skirtingų metodų privalumų, juos surinkti, kad būtų lengva rasti informaciją apie kiekvieną iš jų ir parodyti per metus įvykusią raidą, taip pat pateikti informaciją apie mūsų tyrimus, susijusius su naujo tipo „vaskuliarizuoto“ priekinis kryžminis raištis transplanto kūrimu.

Metodika: Ši magistro darbas yra pagrįstas pasakojimo forma ir atvejų pristatymu. Dauguma straipsnių yra iš pastarųjų dešimties metų; tačiau buvo įtrauktos ir kai kurios senesnės publikacijos, jei jos atrodė aktualios ir naudingos šio darbo kontekstui bei turiniui. Buvo atlikta atvira literatūros paieška, siekiant surinkti pagrindžiančią medžiagą ir ištirti dabartinę priekinis kryžminis raištis raiščių operacijų padėtį. Tyrimai dėl vaskuliarizuotų transplantatų buvo atlikti praktiškai, naudojant lavonų medžiagą.

Rezultatai: Per pastaruosius metus priekinis kryžminis raištis rekonstrukcijos sritis žymiai pažengė į priekį, atsirado daug transplantatų tipų. Mūsų idėja dėl vaskuliarizuoto transplantato galėtų būti perspektyvi alternatyva dabartiniams transplantatams. Reikia atlikti tolesnius tyrimus, siekiant patobulinti chirurginę techniką ir ištirti audinių komplikacijų dažnį. Išvados dėl anatominių struktūrų dydžio yra pagrindas sėkmingam vaskuliarizuoto transplantato naudojimui.

* This page has been translated from the English version of abstract into Lithuanian language using the DeepL Translator from the company DeepL SE. / Šis puslapis buvo išverstas iš anglų kalbos santraukos į lietuvių kalbą naudojant „DeepL Translator“ vertimo programą, sukurtą bendrovės „DeepL SE“.

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Keywords

orthopaedics, acl reconstruction, vascularized graft, microsurgery, knee surgery, sports medicine

1. Introduction

The human knee is comprised of four main ligaments – two collateral ligaments and two cruciate ligaments. The collateral ligaments support the sides of the knee, while the cruciate ligaments are in the centre of the knee. The anterior cruciate ligament, known as ACL, is found within the knee. Together with the posterior cruciate ligament (PCL), they form X inside the knee. The ACL is responsible for preventing the tibia from sliding out of the femur and providing rotational stability to the knee, while the PCL is responsible for keeping the shinbone from moving backwards too far. The ACL is weaker compared to the PCL, leading to it being injured more often.

ACL injury is one of the most dreaded injuries for professional athletes, such as hockey players, as it can be career-ending in the worst-case scenarios; however, with the developments of modern medicine and rehabilitation, getting such an injury is no longer the end of the world.

This master's thesis is a narrative thesis that explores the development of ACL reconstruction using different graft techniques and presents a new type of "vascularized graft". The idea of ACL reconstruction isn't a new idea. Between 1900 and 2000, surgeons performed many successful operations, and techniques developed alongside advances in surgery and clinical medicine. The presented idea of a vascularized graft is in the pioneering stage, and further studies will be needed to evaluate its possibility in a clinical setting. If our proposed idea could work and be used, it could offer a faster-healing graft due to active circulation within the graft, leading to shorter rehabilitation times and getting professional sportsmen back on the field faster, thereby cutting overall rehabilitation costs. The vascularized graft could also withstand greater strain than "dead" grafts used nowadays.

1.1. Methodology

This thesis is a mixture of a narrative thesis and a case report. Its aim is to provide general insight into anterior cruciate ligament reconstruction and to present a new type of graft to be used as a replacement for the anterior cruciate ligament.

The main sources for searching data were PubMed, to support identification of relevant other sources for literature artificial intelligence tools Scite and Consensus App were used. The field of ACL surgery has developed a lot in the 2000s; most of the articles I chose were from the last five years. However, as the idea of the thesis was to give a broad insight while not indulging too deeply, I have included literature materials that were published before the last five years. The included materials have been checked to be relevant to thesis topic and current practices.

The tools used for data gathering and writing were self-taken photographs, an Apple iPhone 13 Pro Max, a Leica surgical microscope, and an Apple MacBook Pro 2023.

The tools for literature gathering and analysis, writing, and compiling the thesis were Microsoft Word (Version 16.106.2), Microsoft Excel (Version 16.107.3), Zotero (Version 7.0.32), for checking and organising the literature materials, Scite by Research Solutions Inc, and Consensus App. For the proofreading, I have used Grammarly and Microsoft Word proofreading.

For Section 5, the cadavers used for the dissection were donated to the Faculty of Medicine, Vilnius University. A separate declaration of patient consent was not required, and the patient's identity was not disclosed or compromised in this thesis.

Financial support and sponsorship

I didn't receive any external funds or sponsorship regarding this thesis.

Conflict of interest

There are no conflicts of interest.

2. Anatomy of a knee joint

2.1. General overview of the knee

The knee is the biggest joint in the human body. It allows us to move by enabling flexion and extension of our lower limbs. The knee joint is formed between the patella, femur and tibia and has a broad range of motion (ROM) and good stability. The most important ligaments providing the stability of the knee joint are the collateral ligaments and the cruciate ligaments – the lateral and medial collateral ligaments, the anterior and posterior cruciate ligaments. As presented in the introduction, those four ligaments are the main ligaments. The main areas we are interested in are the anterior cruciate ligament and genicular arteries, as well as the ligaments in their proximity. As well as the genicular arteries due to our idea of vascularized graft being based on them.

To get us acquainted to the topic, I present anatomical drawings of the structures and dissection images. This chapter will also give guidance in Section 5. The most important landmarks we are looking for in the knee are the bony landmarks needed for correct anatomical reconstruction.

For anatomic reconstruction, a precise understanding of the structures is essential. In an arthroscopic procedure, the surgeon needs to orient themselves with bony landmarks; these landmarks are present even if the ACL has been disintegrated. Most important bony landmarks to be used in ACLR are lateral intercondylar bridge (also known as “residents” ridge), lateral bifurcate ridge. These structures provide important guidance on where the femoral tunnel or tunnels shall be placed. Regarding the site of the ACL ligament, the intercondylar ridge shows the most anterior point of the ACL ligament’s insertion. The bifurcate ridge runs vertically and posterior to the intercondylar ridge; it divides the insertion site for the anterior bundle and the posterior bundle of the ACL ligament (1).

Our idea of a vascularized graft is based on the very characteristics of the placement of genicular arteries surrounding the knee. Without genicular arteries, the whole key idea of a vascularized ACL graft could not be produced.

To acquaint us with important structural parts of the knee, I am using images from the Stanford University Medical History Collections archive, which holds the copyright to the originals of David L. Basset's anatomical images (©2006, SUMMIT Stanford University, Basset Collection). The usage of the images is under the CC BY-SA 4.0 licence. The images originate from a collection named “Dissection of the knee”. The used images are in figures 1-1, 1-2, 1-3, and 1-4.

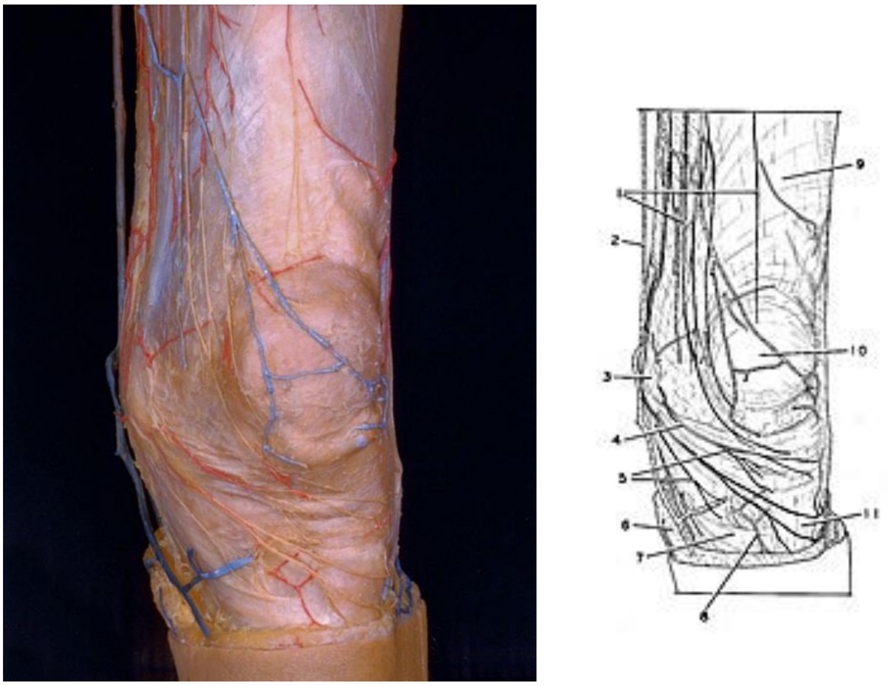

Figure 1- 1 Fascia lata seen on right knee

Figure 1-1 shows the fascia lata layer and its superficial (on the top) structures.

Structures to be seen 1. Cutaneous branches of the anterior femoral nerve; 2. Greater saphenous vein; 3. Medical epicondyle; 4. Saphenous branch of descending genicular artery; 5. Infrapatellar branch of the saphenous nerve; 6. Tela subcutaea; 7. Tendon of insertion of the sartorius muscle; 8. Anterior tibial recurrent artery; 9. Fascia lata; 10. Patella; 11. Insertion of the patellar ligament on the tibial tuberosity.

Understanding how the ligaments of the knee and the knee capsule are formed is necessary for ACL surgery. Therefore, let's explore the knee capsule from anterior, lateral, posterior and medial views.

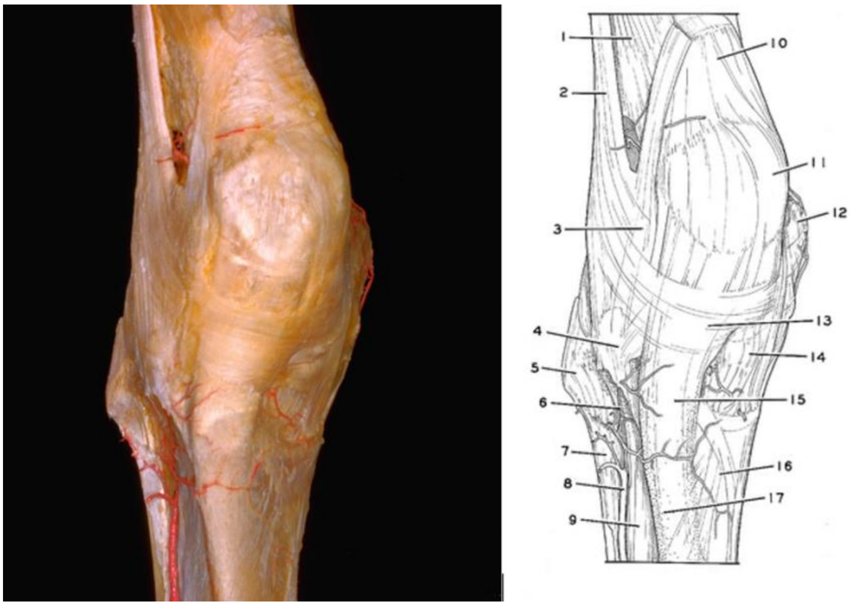

Figure 1- 2 Anterior aspect of right knee

The figure 1-2 shows the anterior view of the knee capsule and the structures numbered: 1. Vastus lateralis muscle; 2. Iliotibial tract; 3. Lateral patellar reticulum; 4. Lateral condyle of tibia; 5. Head of fibula; 6. Anterior tibial recurrent artery; 7. Body of fibula; 8. Anterior tibial artery; 9. Interosseous membrane of the leg; 10. Quadriceps tendon; 11. Patella; 12. Medial epicondyle of tibia; 13. patellar ligament; 14. Medical condyle of tibia; 15. Tibial tuberosity; 16. Crural fascia; 17. Anterior border of the tibia.

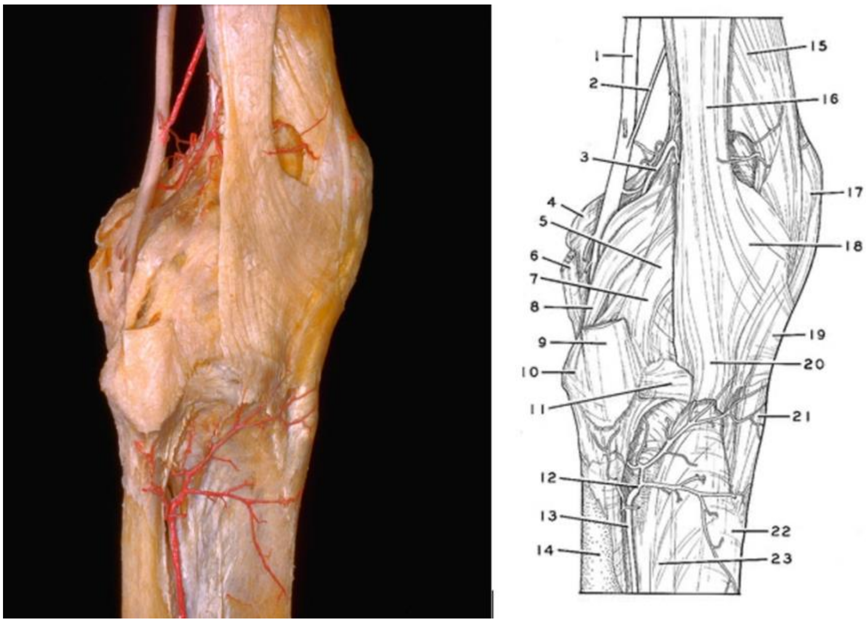

Figure 1- 3 Lateral view of the right knee capsule

In Figure 1-3, the latter view of the knee capsule shows 1. Popliteal artery; 2. Muscular branch of the popliteal artery; 3. Lateral superior genicular artery; 4. Medial condyle of a femur; 5. Lateral condyle of a femur; 6. Semitendinosus muscle; 7. Collateral ligament of the fibula; 8. Popliteal arcuate ligament; 9. Biceps femoris muscle; 10. Head of fibula; 11. anterior head of muscle ligament; 12. Anterior tibial recurrent artery; 13. Anterior tibial artery; 14. Body of fibula; 15. Vastus lateralis muscle; 16. Iliotibial tract; 17. patella; 18. Lateral patellar retinaculum; 19. Patellar ligament; 20. Lateral condyle of tibia; 21. Tibial tuberosity; 22. Body of tibia; 23. Interosseous membrane of the leg

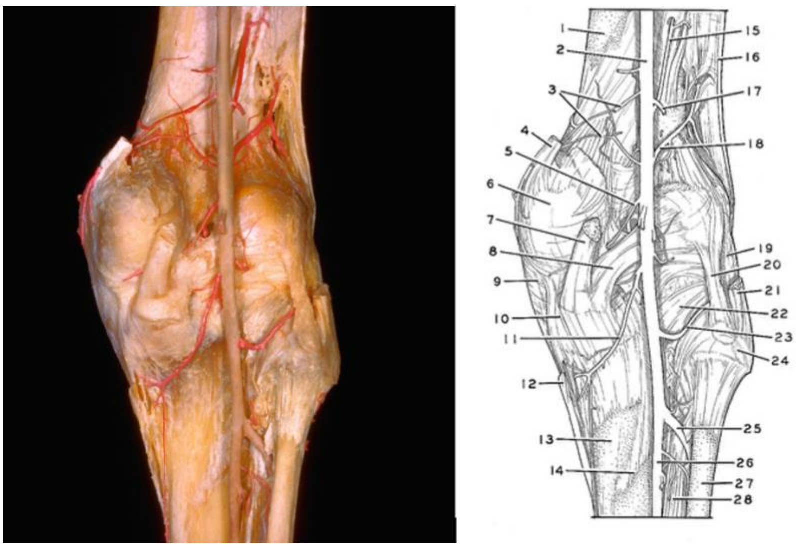

Figure 1- 4 Posterior view of the right knee capsule

In Figure 1-4, the posterior view of the knee capsule is shown. I would emphasise paying close attention to the genicular arteries, as our section 6 of this thesis will focus on vascularized grafts and the genicular arteries, and this is one of the core ideas. The structures seen: 1. Body of femur; 2. Popliteal artery; 3. Lateral superior genicular arteries; 4. Adductor magnus muscle; 5. Medial genicular artery; 6. Medical condyle of a femur; 7. Semimembranosus muscle; 8. Oblique popliteal ligament; 9. Collateral ligament of the tibia; 10. Medial condyle of tibia; 11. Lateral inferior genicular artery; 12. Semitendinosus muscle; 13. Body of tibia; 14. Soleal line; 15. Muscular branch of the popliteal artery; 16. Iliotibial tract; 17. Descending genicular artery; 18. Medial superior genicular artery; 19. Collateral ligament of the fibula; 20. Popliteal arcuate ligament; 21. Biceps fern oris muscle; 22. Popliteus muscle; 23. Medial inferior genicular artery; 24. Head of fibula; 25. Anterior tibial artery; 26. Posterior tibial artery; 27. Body of fibula; 28. Interosseous membrane of the leg.

Now that the anterior, lateral and posterior views are coved we still must cover the medial side of the knee capsule.

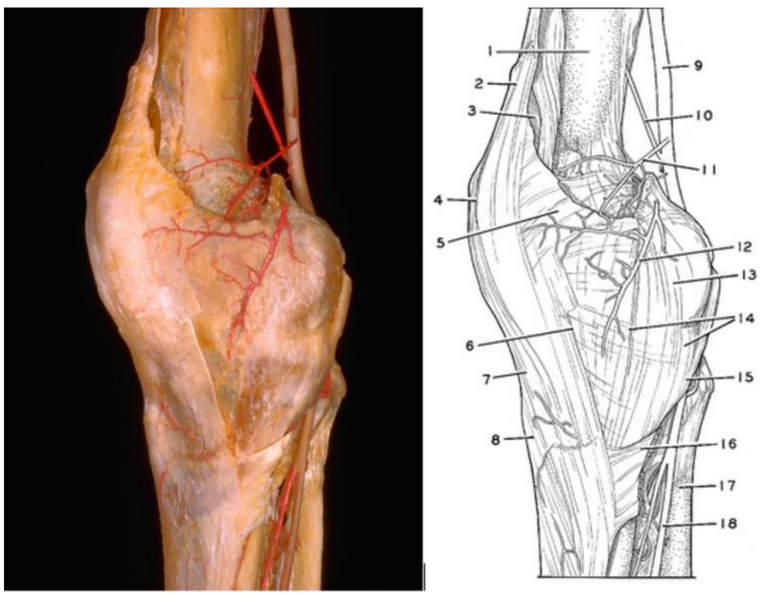

Figure 1- 5 Medial view of the right knee capsule

In Figure 1-5, the medial view of a right knee capsule is shown with structures: 1. Body of femur; 2. Tendon of the quadriceps muscle; 3. Opened suprapatellar bursa; 4. Patella; 5. Articular capsule genus; 6. Medical patellar retinaculum (cut-off); 7. Patellar ligament; 8. Tibial tuberosity; 9. Popliteal artery; 10. Muscular branch of the popliteal artery; 11. Medial superior genicular artery; 12. Branch of descending genicular artery; 13. Medial condyle of femur; 14. Collateral ligament of the tibia; 15. Medial condyle of tibia; 16. Tendons of insertion of sartorius, gracilis and semitendinosus muscles; 17. Body of fibula; 18. Posterior tibial artery.

To look deeper into the structures, I am presenting a picture of the inside of the knee, from inside the fascia lata.

The figure below, Figure 1-6, is an anterior view of the knee joint dissection, showing the collateral ligaments, the anterior cruciate ligament, and the posterior cruciate ligament. The figure is taken from File: Slide2CAC.JPG. (2020, September 3). *Wikimedia Commons*. Retrieved March 14, 2026, from https://commons.wikimedia.org/w/index.php?title=File:Slide2CAC.JPG&oldid=447265836.

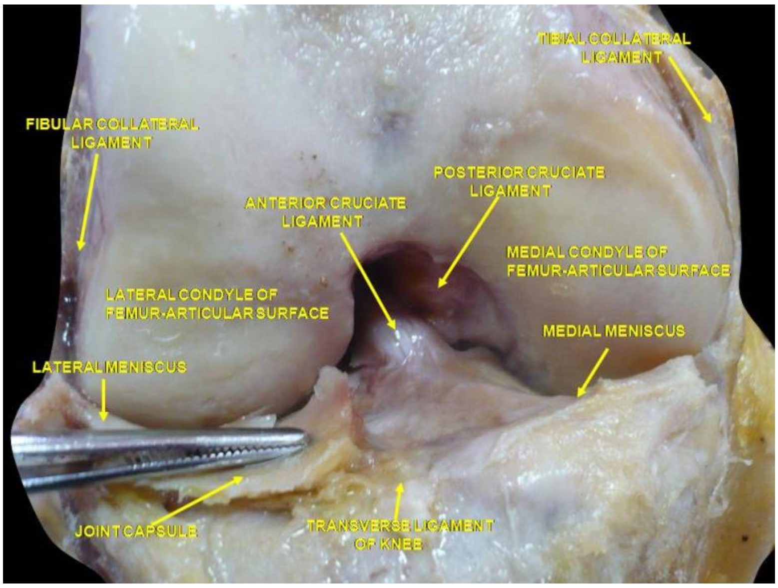

Figure 1- 6 Anatomical dissection of the knee (anterior view)

How about the posterior aspect of a knee? On the posterior side, we can't see the anterior cruciate ligament, but the posterior cruciate ligament is visible together with the ligament of Wrisberg. Figure 1-7 shows the left knee joint from the posterior aspect. The figure is taken from File: Gray348.png. (2022, July 2). Wikimedia Commons. Retrieved March 14, 2026, from https://commons.wikimedia.org/w/index.php?title=File:Gray348.png&oldid=670794204

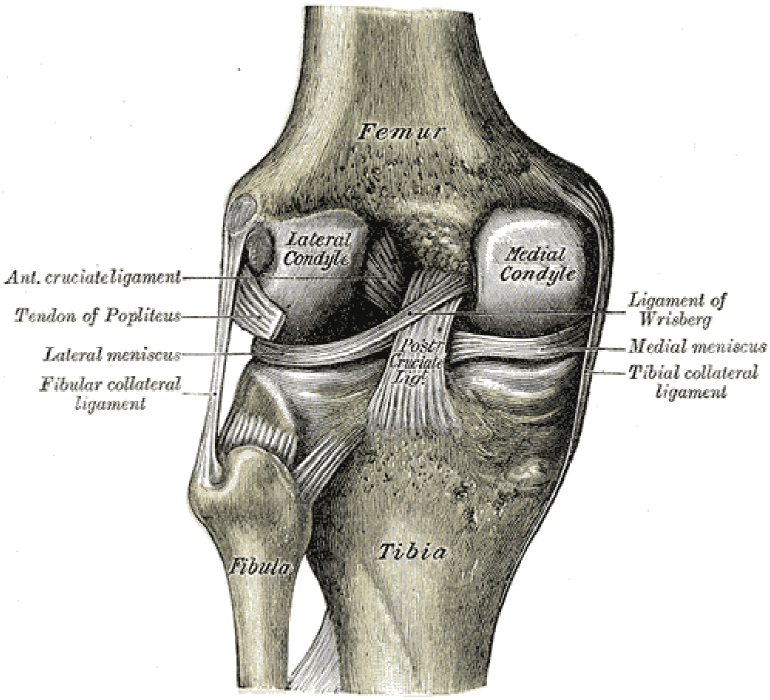

Figure 1- 7 Posterior aspect of the knee showing the inferior ligaments

The idea of creating a vascularized graft leads to vascular structures of the knee. The genicular arteries, with the anterior tibial recurrent artery, form a vast arterial network around the patella. To visualise the arteries, I am showing figures 1-8, 1-9 and 1-10 from Insall & Scott's book "Surgery of the Knee, " 4th edition (2). The arterial circle surrounding the patella is made by the anterior tibial recurrent artery, the inferior lateral genicular artery, the superior lateral genicular artery, the descending branch of the lateral circumflex femoral artery, the descending genicular artery's articular branch, the superior medial genicular artery, the descending genicular artery's saphenous branch and the inferior medial genicular artery.

As said earlier the key idea behind our vascularized graft is using the genicular arteries. To take sufficient arterial piece from the medial genicular artery and later connect it to the lateral genicular arteries. The genicular arteries provide supply from multiple parts, making it possible to detach part of the arteries and make anastomoses without affecting the blood sources of the nearby tissues.

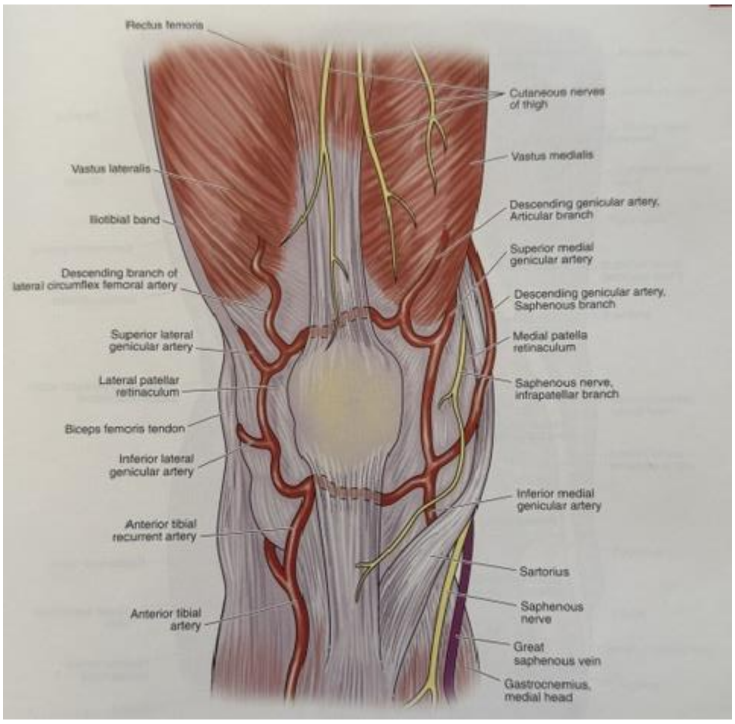

Figure 1- 8 Superficial structures of the anterior aspect of the knee

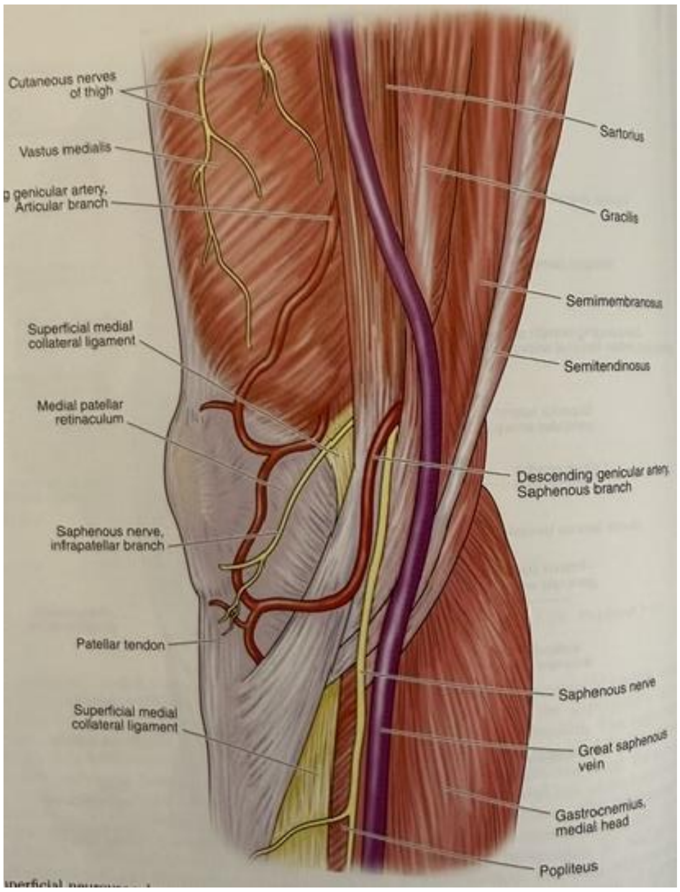

Figure 1- 9 Superficial structures of the anteromedial aspect of the knee

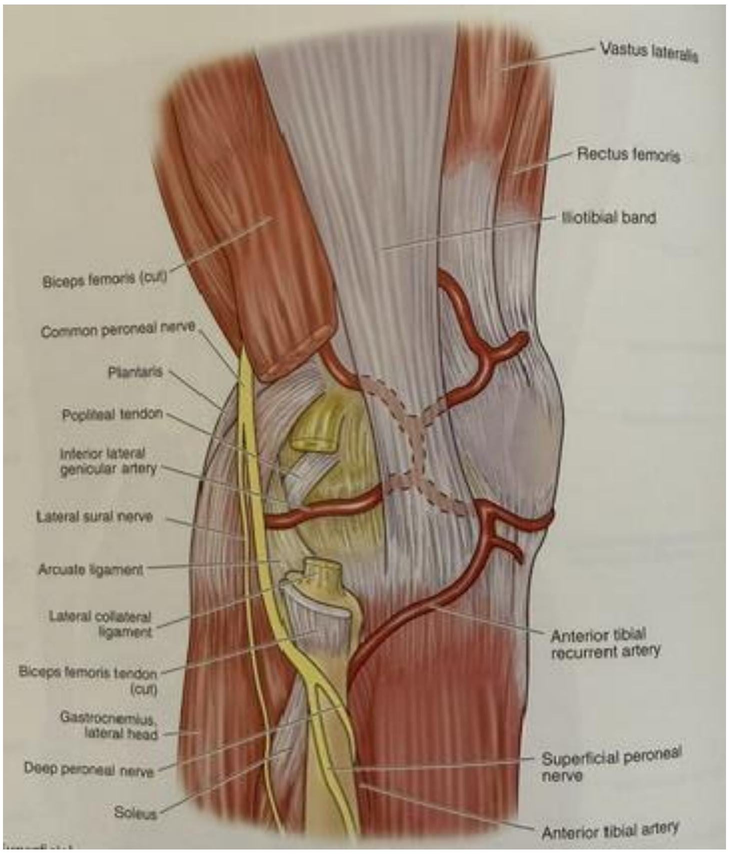

Figure 1- 10 Superficial structures of the lateral aspect of the knee

2.2. Properties of structures

Properties of various landmarks

ACL ligament

The ACL ligament is compromised from two functional bundles: the anterio-medial bundles (referred as AM) and the posterio-lateral bundles (referred as PL), this has been confirmed in fetal, arthroscopic and cadaveric studies according to Chhabra A. et al. (3). The figure 2-1 is reproduced from their paper.

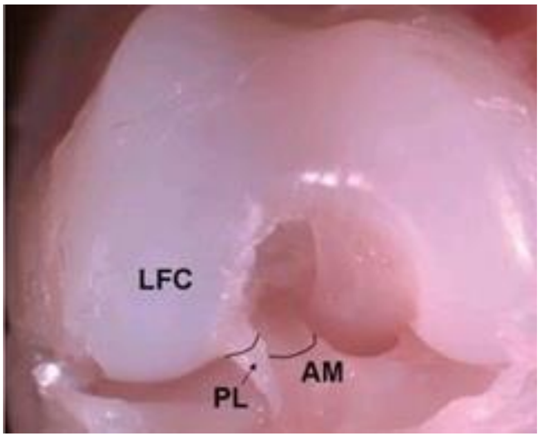

Figure 2 - 1 Fetal knee showing AM, PL and LFC

The LFC means lateral femoral condyle. The AM anteriomedial bundles and the PL posteriomedial bundle.

The ACL ligament is inserted between the femur and the tibia. Insertion sites are variable across the patient population. In a study by Kopf et al. (4) the variation in tibial and femoral insertion sites among 137 patients undergoing primary anterior cruciate ligament reconstruction was described. Kopf et al. found that the tibial insertion site varied between 16 and 18 mm and the femoral insertion site between 16 and 18 mm (4).

3. ACL injuries

ACL injuries are among the most frequently studied knee ligament injuries in the world, with diverse populations with variations regarding sport, leading to injury, sex, age, and geographic region. From a general standpoint, injuries are more common among people who engage in high levels of physical activity and participate in sports. Most ACL injuries occur in the active population engaged in various sports (5–7). Most frequent injuries happen among sportsmen and sportswomen in soccer, basketball, volleyball, handball and alpine skiing, according to Strobel et al. (8).

From the population variables, we can see age- and sex-related patterns. Not just in the adult population, ACL injuries are seen in youth and children who are active in sports. In recent decades, the participation of children and youth in various sports has increased, leading to higher rates of documented ACL injuries (9). From an epidemiological standpoint, CLI are well studied in paediatric populations in Europe and the USA, but remains under-researched in Asian countries such as China, according to Zhi et al. (10). In the sex-related patterns, the female gender is associated with an increased risk in the population of female athletes throughout various sports. Studies from Dolk et al.(11), Axelrod et al. (12) and Guy et al. (13), show higher incidence of ACL-injuries and ACLR on female athletes compared to men athletes as well as on paediatric population (9).

Anatomy itself can serve as a risk factor. In the knee joint, many anatomic peculiarities and individual differences are present. In a systematic review of "Knee Morphological Risk Factors for Anterior Cruciate Ligament Injury" (14), S. Bayer et al. described the following key anatomical risk factors: "Knee morphology, particularly intercondylar notch stenosis, variations in sagittal condylar shape, increased tibial slope, reduced tibial eminence size, poor tibiofemoral congruity, and reduced ACL size". Also, Strobel et al. in their book described similar risk factors, such as a small intercondylar notch width index, generalised joint laxity, increased BMI (in women), and machine tests indicating knee joint laxity outside the standard deviation of the mean (8).

ACL injuries are categorised into contact and noncontact injuries. In the general population, one who hasn't read about the field could think the main cause of ACL injury in athletes would be from external trauma. However, the research shows that direct trauma (contact injury) plays a role in only 30% of the ACL injuries, as 70% of the cases are from non-direct trauma (non-contact injury) (8). In contact, the injury results from the effect of an external force, such as contact with another athlete; in non-contact, there is no external force (15). Also, ACL injuries can be classified by cause, according to Strobel et al. (8). Several mechanisms of injury are known:

1. External rotation – flexion – valgus trauma
2. Internal rotation – flexion – varus trauma
3. Hyperextension trauma
4. Hyperflexion trauma

The mechanisms leading to ACL injuries arise from the forces the ACL experiences during noncontact pivoting, deceleration, rapid changes in direction, and landing manoeuvres. Such mechanisms are frequently reported through different sports and age groups. In the paediatric population, the most predominant mechanism is sprain (10–12).

In noncontact pivoting, the foot stays planted, but the body shifts position, creating tension and forces that the knee ligaments must endure under the person's load. During deceleration, ligament injury can occur from a sudden stop, cutting, or landing with a slightly bent knee, which can subject the ligaments to high torsional/valgus forces. During sudden directional changes, the knee twists, as during deceleration. When the knee is not fully extended, the ACL is under tension and at higher risk of damage.

4. ACL reconstruction

Due to the knee capsule's local intra-auricular conditions, the ACL has a poor capacity to heal on its own compared to other tissues in the human body. In ACL injury, the gold standard for primary ACL reconstruction is surgery using an autograft from either the hamstring tendon or the patellar tendon (16). In the USA, the ACL reconstruction is the most common method for treating ACL injuries (17).

The goal of ACL reconstruction is to replace the torn ACL ligament with a graft to restore knee stability. In the current ACLR landscape, many types of grafts can be used. If the graft comes from the patient, it is an autograft. The autograft can be formed from a person’s own iliotibial-, quadriceps- or patellar ligament, which is used to replace the damaged ACL ligament. If the graft comes from a donor, it is an allograft. The graft can also be a synthetic graft (non-biological material) (18,19).

As presented in Section 2, Anatomy of the knee joint and its subsequent properties, where the ACL is located, in ACL reconstruction, the graft is attached to the femur and the tibia. As there are many graft types, there are various ways to attach grafts.

The attachment must be firm, so the new ACL doesn’t fail and the knee stays stable. It requires healing of the bone and ligament. Fixation is the process of attaching tissues to one another. In terms of mechanical fixation, there are two principles: fixation into the tunnel and cortical fixation. Also, post- or extra-cortical fixation can be used. It is also possible to combine various approaches in a hybrid fixation.

Compression fixation / Interference (Aperture) fixation

- Usage of interference screws (metal or bio-absorbable) to wedge the graft against the tunnel wall inside the bone (20–22).
  - Options include cross-pins, press-fit, and sheath screws (20)

Suspensory (Cortical) fixation

- Usage of a button on the outer surface of the bone, connected by sutures or loops (fixed loop, adjustable loop devices) (20,23–26).
- Usable on the femur, tibia or both. (Common in all-inside techniques) (23,24,26).

Post / Extra cortical fixation

- Sutures tied over a post, a screw + washer or a bone ridge on the tibia (22,23).

Hybrid fixation

- Combines the above-mentioned methods, e.g. suspensory button + interference screw for added stability (21,23).

Table 1 - 1 Graft fixation methods and sites

Site	**Common Attachment types**	**Advantages / Disadvantages**	**Cited**
Femur	Cortical button (fixed/adjustable loop), cross-pin, interference screw	Cortical buttons preferred by many surgeons. Rigid compression less motion.	(22–24,26)
Tibia	Bioabsorbable or metal interference screw, cortical button, bone bridge, hybrid screw + button or screw + bone bridge	Tibial fixation often seemed to be weak link. Rigid compression, less motion.	(21,23,26)
All-inside ACLR	Suspensory fixation both sides with adjustable-loop buttons; often with supplementary sutures/tape	Less invasive surgery and adjustable tensioning.	(23,24)

The common factor for various graft attachment types and grafts is that graft healing usually takes a long time to heal. Patients most often need a long 9-12-month rehabilitation period before returning to the stage prior to the ACL injury, so the ACL ligament has time to heal and become biochemically equivalent to the native ACL ligament (27).

4.1. Typical grafts used for ACL reconstruction

The most used and generally preferred grafts in ACLR are autografts from the hamstring tendon (HT), the bone-patellar tendon-bone (BPTB), and the quadriceps tendon (QT). Less commonly used and not widely adopted are autografts from the Achilles and tibialis tendons (19,28–30).

Allografts, as presented earlier, are from donor tissue, often from cadaveric tissue. Usually, tibialis anterior/posterior, Achilles, peroneal, BPTB, and hamstrings are used (28,29).

For synthetic grafts, non-biological materials are used, such as LARS, polyester-based devices, Dacron, carbon, and polypropylene (28,31).

In narrative and clinical reviews that reflect actual use in surgeries, biological grafts are preferred for their trustworthiness (18,32).

All the graft types have their own source, being tissue or synthetically made, and all of them are adopted differently. From the literature sources used for this thesis, I have compiled a table for us to easily understand some of the differences, the table 1-2 Graft types is presented below.

Table 1 - 2 Graft types

Graft type	**Typical tissue source**	**Usage**
BPTB / BTB	Central patellar tendon + bone blocks	Long used “golden standard”
HT	Semitendinosus ± gracilis	Largely adopted, worldwide usage
QT	Quadriceps tendon ± bone	Increasing use
Allograft tendons	Tibialis, Achilles, BPTB, hamstring, peroneal (from donor)	Often in revisions and with older patients
Synthetic ligaments	Polyester-based devices (e.g., LARS)	Limited, selective use

BPTB/BTB graft

Bone- patellar tendon-bone graft (BPTB) or simplified bone-to-bone (BTB) graft is the “golden" standard used around the world. Still a popular variant, but on a worldwide usage, a second after Tuca et al. study (33). BPTB is considered to provide strong, reliable stability for the knee, to heal well in athletes and resist pivoting, and to have a long clinical track record of good functionality, good return-to-sport rates, and durability of stability (34,35).

- ⇨ Wide usage historically and still very common.
- ⇨ Commonly favoured for high-ranking “elite” athletes.
- ⇨ Higher risk of anterior knee pain compared to HT grafts.

HT graft

Hamstring tendon graft is typically harvested from the semitendinosus and/or gracilis tendons on the inside of the thigh. Widely used for primary ACL reconstruction and revision (36). Based on recent worldwide studies on preferences for ACLR by Tucá et al. (33), the HT graft is now the most recommended option for ACLR. The HT graft enables return to sports after 8.9 months. The HT graft is also associated with less anterior knee pain compared to BPTB grafts (37–39).

- ⇨ Increasing usage around the world, possibly the new “BPTB/BTP graft” of the current time.
- ⇨ Less anterior knee pain than in BPTB, but the choice depends on the surgeon, technique and patient activity before surgery.

QT graft

Quadriceps tendon ± bone grafts have increased use, serving as a major “third” option alongside the above BPTB and HT grafts. Overall failure rates seem similar, while some analyses show slightly lower failure rates associated with the QT graft used in ACLR (22). Knee stability is comparable to that of the above-mentioned grafts (36).

- ⇨ Not as popular as the BPTB grafts and HT grafts, but it shows excellent clinical results with low morbidity.

Allografts

Allograft tendons are obtained from a donor. The usual allograft tendons are Tibialis, Achilles, BPTB, Hamstring, and Peroneal. Often used in revisions and with older patients (22). The advantage of allografts over autografts is that they do not present donor-site pain (if a dead donor is used), but in many respects, autografts are better in terms of healing and synovialization. Allografts have a higher failure risk. Also, the cost of allografts is higher than that of autografts (40).

- ⇨ Safer and more available with improved sterilisation.
- ⇨ Slower biological incorporation than with autografts.
- ⇨ Chosen often for low-demand individuals and revisions.

Synthetic ligaments

Early synthetic grafts using materials such as carbon fibre, polypropylene, and Dacron showed high failure rates, leading to their withdrawal from recurrent usage (41). The old synthetic ligaments have a higher failure rate than current autograft variants, often with synovitis, tunnel widening, poor tendon to bone integration, and loosening (32). From a theoretical standpoint, artificial materials would offer benefits, such as no harvest morbidity (which can be associated with biological grafts) and rapid rehabilitation, but in research, the disadvantages have been more notable due to high failure rates. However, synthetic materials can be used not just on their own but alongside biological materials to gain benefits from both, as in augmentation, as in LARS.

- ⇨ Old synthetic variants have higher failure rates than biological grafts.
- ⇨ Possible advantages in hybrid methods where synthetic material is used as augmentation.

4.2. Typical problems with the grafts

4.2.1. Problems of ACL reconstruction in children

ACL injuries also happen in the paediatric population with an increasing rate, according to Zhi et al. (10). Anterior cruciate ligament reconstruction is also used for treatment. In the paediatric population, there are some differences in the risks associated with ACLR compared with the adult population. The main risks are growth-related complications and high rates of graft failures and repeat injuries. In growth-related complications, premature physeal closure, limb-length discrepancies plus angular deformities (valgus) can occur with any ACL reconstruction technique (42). In graft failures, studies show higher rupture rates than in adults, with increased re-ruptures and a need for revision (43). Joint damage is seen in meniscal tears, cartilage injuries and with degenerative changes, especially with non-operative and delayed surgery, according to Jin et al. (42).

4.2.2. Restoring original anatomical function – anatomical challenges

In ACLR, the goal of surgery is to restore the original function. By restoring the overall function of the ACL ligament, the stability of the knee is restored. To reach the goal, the overall anatomy and biomechanics are being recreated. Across the literature, there are key anatomical challenges, one being drilling the femoral tunnel too high/ too anteroproximal, leading to residual laxity, abnormal motion, and cartilage thinning (44). These points linked to transtibial drilling are sought to cause AP and rotary instability, higher revision risks and worse clinical outcomes, as well as increased occurrence of osteoarthritis. The second key anatomical challenge is drilling the tibial tunnel into malposition, too high/too medial, leading to the graft no longer being an anatomical graft and altered forces in structures (45). The third key anatomical challenge is following the exact footprint, as by missing the footprint of tunnels, the kinematics can change, leading to graft not working as wanted (44).

According to Tashman et al. (44) even in well performed single and double bundle anterior cruciate ligament reconstructions the exact anatomical function is not achieved however close to it is reached. AP stability is often achieved, but rotational stability is often not, with the latter leading to problems due to persistent ACL injury and later osteoarthritis (44,45).

4.2.3. Outcomes after the graft surgery with different graft methods

Grafts used today provide nearly the same knee stability and patient-reported outcomes. However, the research shows differences among grafts in failure risk, donor-site morbidity, strength profiles, and return-to-sport profiles. The current research provides the strongest evidence for BPTB and HT grafts, which are widely adopted, but QT grafts and synthetics still lack sufficient data, as they have not been investigated as extensively.

To sum up Chapter 4, I have compiled a table to easily differentiate the main clinical outcomes by graft type. In the table, different grafts are compared based on 1) failure/laxity, 2) donor site morbidity and pain, 3) function, PROs and RTS.

Table 1 - 3 Graft types: main outcomes by graft type

Graft type	Failure / Laxity	Donor-site morbidity and pain	Function, PROs and RTS
BPTB autograft	Among lowest failure	Highest anterior knee-pain and kneeling difficulties.	Highest RTS (~81%) in high-level evidence (35). PRO similar to others (35)08/05/2026 04:32:00
HT autograft	Higher failure than BPTB in many series (up to 11–17%) (39). Slightly better laxity than in synthetics (22).	Lower anterior knee/kneeling pain than BPTB	RTS often lower (~52%) vs BPTB (33). PROs generally comparable (35).

Table 1-3 Graft types: main outcomes by graft type (continues)

QT autograft	Failure similar to BPTB/HT; some meta-analyses show lower failure vs HT (35). Good stability (35).	Lowest donor-site morbidity vs BPTB and often vs HT (22,35).	PROs and laxity equivalent to BPTB/HT (46).
Autograft vs allograft (primary/revision)	In revision allografts have higher risk of failure. However, laxity and similar PROs. (however, some sources say the allografts laxity is decreased compared to autograft)	Allograft is sterile, less risks for infection and immune problems.	
Synthetic	Some modern synthetics show similar short- to mid-term stability and failure to autograft (39). Older synthetic grafts had higher failures compared to other grafts (41).	No harvest morbidity; device-related complications possible (22). Higher risk on older synthetic materials to cause synovitis etc. (32).	Functional scores largely comparable to autograft (22).

In the table, the actual grafts are BPTP, HT, and QT grafts; all of them can be either autografts or allografts. On top of them are synthetic grafts, as presented earlier. From the table, we can see that the BPTB graft is the best of them all, with the lowest failure rate and the highest return-to-sport rate. While superior with low failure rates and a good option for elite athletes, the BPTB is associated with higher rates of anterior knee pain. The HT and QT grafts don’t have such a level of anterior knee pain.

4.3. Evolution of ACL-ligament graft choices throughout history

In the last decade, modern medicine as we know it has seen considerable development. Not just the innovative new drugs, but also clinical medicine and surgical approaches have developed over the years. The development has been from early tendon grafts to modern, current-day individualised options.

From a historical and clinical standpoint, ACL grafts have evolved from experimental fascia and tendon repairs to a few dominant autografts (BPTB/BTP, HT, QT), with synthetic grafts remaining experimental and not a “single best graft”. A lot has happened during the years, and I am showing the development split into easily understandable time periods. Before going to the 1900s, when most of the innovation occurred, let’s go back to the Egyptian era. The Edwin Smith Papyrus was created around 1600 BCE. It's considered one of the milestones in medicine and surgery of its time. In the paper, the cruciate ligaments were first described (47,48). After the Egyptians, the Greek doctor C. Galen described the biomechanics of the knee and the role of the ACL (38,48). Up till 19th century, the tales of ACL were widely unknown, in 1836 German brothers Eduard Weber and Ernst Weber, anatomist - physiologist and physiologist (49), created a book “Mechanik der menschlichen Gehwerkzeuge” in English “Mechanics of Walking in humans”, where they identified ACL being comprised from two bundles (AM and PM) (38). Later in 1845, French surgeon A. Bonnet treated a variety of blood knees and provided insight into ACL lesions, proposing conservative treatment at the time (38). Until the end of the 19th century, interest in ACL grew, and at the beginning of the 20th century, the first ACL repair was reported by Battle, performed by Mayo-Robson (16,38). The open technique gained popularity, and the first repairs were done in a primary fashion.

Autologous fascia and meniscal grafts were first reported in 1912 by K.H. Giertz, and later by H. Groves and Smith (38). The new method gained popularity, and in 1934, new innovations were made in Italy. In Italy, the first hamstring tendon graft was developed originally by R. Galeazzi, and later, in 1939, Macey reproduced his research (38,48).

Patellar tendon grafts were first reported by Campbell in 1935; however, his technique initially failed, and it was later reproduced by Macintosh, who became more interested in the topic (38,48). As time passed, Kenneth Jones developed a revised version in 1963 that involved creating a bone-patellar tendon-bone graft (38,48). Jones paved the way for this new kind of graft, but with refinements later made by Brückner, Franke, Marshall et al., it became the gold standard of treatment for ACL injuries in the 1990s (38,48).

Early synthetic grafts made of carbon came into use during the 1970s and 1980s; the first carbon-based grafts were thought to be a perfect material, as our cells are also made of carbon. The first experiments were conducted by David J. Dandy at the University of Cambridge (38,48). The first experiments were conducted on animals before proceeding to human trials. In human trials, the first results showed potential healing in knees, but later the carbon-based methods were omitted as it became apparent that they increased the risk of knee synovitis and caused complications (38,48). Later, the other synthetic materials were investigated and developed (different synthetic materials presented in section 4.2.).

Allografts rose to the minds of the scientists in the 1980s for ACLR. First studies were done on animals – dogs, by Webster and Werner in 1983 (38,48); they used freeze-fried tendons which were rehydrated and implanted in ACLR. The preliminary results of their research showed potential for graft properties similar to those of patellar tendon grafts (38,48). Later, Curtis et al. received similar results when replicating the study. Histological testing was done showing the "dead ligaments" became "alive" through revascularisation and fibrovascular creeping (38,48). The grafts served as a biological scaffold, on which the recipients' bodies would begin to build cells to bring it to life. Nowadays, such an effect is sought after in biological augmentation on hybrid techniques. To enhance revascularization and fibrovascular creeping to make a graft and graft attachment sites to bones heal faster biological methods such stem cell therapies, growth factors, biomaterials can be used (50).

A lot has happened during the 20th century, including the development of the open primary method for anterior cruciate repair before the gold standard (16). Just before the arthroscopic methods gained popularity. The first arthroscopic ACLR was performed by David J. Dandy in Cambridge, with his research on implanted carbon fibre filament (38). In current times, arthroscopic methods are ruling the field of orthopaedics, and surgery is moving more in a minimally invasive direction. Not just in orthopaedics but in many other areas, innovation has shaped the field of surgery as we know it. Learning the process behind surgical innovation is fascinating, and to make new inventions and methods, understanding the history to learn what could be perfected and what has not been researched is essential.

To where have arrived after all this history behind. It has shaped the practices around the world. In the era of modern medicine, the graft choice for anterior cruciate ligament reconstruction is based according to individual needs and various characteristics. Nowadays, it's important to consider the individual's gender, sport type, and level of activity. What kind of athlete is the individual? What kind of risks are there for recurrent ACL injury? I presented earlier how the different sport types and gender can pose a risk to ACL injury. As medicine is in constant evolution, new ideas arise from clinical practice and experiments. Therefore, in the upcoming chapter of my thesis, I present the idea of a vascularized graft, which could, in a favourable scenario, shape the future of ACL reconstruction.

5. Idea of a vascularized graft

5.1. Coming to the idea of a vascularized graft

The idea of vascularized graft comes from thinking that the current graft landscape, whether using the allografts or autografts (biological grafts such as BPTB/BTB, HT, QT), the ligament must go through revascularisation and ligamentization in the healing period. The process of a "dead" graft to become biologically similar to a normal ACL ligament takes around 1 year (27). In the process of graft healings, "revascularization and ligamentization", there are many biological processes going on. According to Yao et al. (50), these biological processes could be categorised into three distinct healing phases: 1) early healing, 2) proliferation and 3) maturation phases. The biological processes include localised "inflammatory response in the tissue, graft necrosis, revascularisation, cell repopulation, osseous integration, collagen remodelling, and ligamentization"(50). According to Yao et al. the three healing phases are:

1) **Early healing**
   - Host response: inflammation.
   - Graft response: cell necrosis.
   - Inflammation occurs when foreign materials are inserted into unusual areas. Inflammation causes cell necrosis, together with impaired vascularisation and depletion of oxygen and nutrients.
2) **Proliferation phase**
   - Host response: angiogenesis.
   - Graft response: cell repopulation.
   - Osteoprogenitors and fibroblasts dominate the necrotic graft tissue to create neovascularisation to bring oxygen and nutrients.
3) **Maturation phase**
   - Host response: tunnel closure.
   - Graft response: matrix remodelling.
   - Repopulated cells from the proliferation phase create matrix remodelling and exhibit variations regarding biochemical and mechanical properties (49).

To explain things in a summarised and easy-to-comprehend fashion from Falconiero et al. (27) and Yao et al. (49), the graft healing needs the body's (graft recipients) own cells to infiltrate the graft to provide a scaffold for the actual ligamentization into a biochemically and mechanically comparable structure as the native ACL ligament. Time is needed for that process.

Time can be a big problem for some individuals, as we all don't have enough time to wait for the process to happen. Let's imagine an NHL player playing ice hockey with good performance and in the middle of their career's top moments. The ACL injury can be devastating for the athlete due to missed time in the hockey rink and missed financial resources. If there was a way to reduce the healing time typically seen in auto and allografts, rehabilitation and healing time would be shorter, and the player would return to sports sooner, producing financial savings.

In our research with my thesis supervisor Assist. Prof. MD. Vytautas Tutkus, PhD., we have researched the possibility of creating a vascularized ligament. Our idea of a vascularized ligament could, in theory, provide shorter healing and rehabilitation times compared to currently available grafts. As we covered the different types of grafts earlier, our graft is a version of a BTB graft (bone-tendon-bone graft), more precisely a version of a BPTB graft (bone-patellar tendon-bone) graft, but with a difference whereby our graft would be kept alive from the very beginning. We would combine the benefits of a BTB graft with the vascular connections, keeping the graft alive and supplied with oxygen and nutrients. In theory, the phases described by Falconiero et al. (27) and Yao et al. (50) would be shortened due to the vascular connections our graft would have from the outset, thereby preventing tissue necrosis.

5.2. Vascularized graft

The research on making vascularized grafts began at the end of 2022, when V. Tutkus and I discussed the dissections and idealised the graft on paper and in discussions. We wanted to explore the possibility of creating a graft from the patellar ligament with the superficial fascia lata and its arteries to be used to create the ACL ligament, which would be supplied via the superficial tissue transferred together with the graft, and explore the possibility of creating anastomoses to make it possible to supply the graft with blood. The graft would be a BPTB graft, with the proximal head from the patellar bone, the patellar ligament between, and the distal part from the tibia. In theory, the patellar ligament is a wide ligament, previously used in BPTB grafts, that could let us take a central piece of it without damaging the biomechanics and integrity of the knee capsule.

After idealising our concept of a vascularized graft, we quickly moved on to cadaveric studies. With the permission of the AHA department of the Faculty of Medicine, Vilnius University, we got access to use cadavers in our research. The department's permit allows the use of donated cadaver material for biomedical research conducted under supervision at the Faculty of Medicine, Vilnius University. The separate permits from the families of the cadavers were not needed, as the cadavers were testamentary/donated to the Faculty of Medicine to be used for biomedical research and teaching of anatomy for medical students. Also, the cadavers were kept anonymised, and the material used for the thesis was captured in a way that an individual can't be recognised from the material. The dissections were done in the dissection cathedral of the AHA department of the Faculty of Medicine in Vilnius University.

In total, two cadavers and three knees were used for the research. The limiting factor for using the cadavers was their availability, as the university needed donations for them. The first cadaver was preserved in formalin for a period of ± half a year; we used both knees from this cadaver. The second cadaver was frozen without formalin conservation; only one knee was frozen. Through the process, we discovered that the frozen cadavers were superior to formalin-conserved ones, as the tissue visibility and structures were more real-life-like. On formalin, the fat was coloured deeply yellow, and some of the fine characteristics were "melted" away.

The general idea for the dissection was to dissect the knee step by step, allowing us to identify anatomical structures and locate the ones we would use according to our theory. The main structures we were looking for were the patellar ligament and the fascia lata/superficial fat tissue overlying it, the genicular arteries, and the bony landmarks presented earlier in the anatomy section. The goal was to detach a graft with an arterial piece, ensure the graft would be sized to function as an ACL, and identify ways to create anastomoses to ensure blood supply to the piece.

Starting with cadaver 1, we prepared surgical instruments, a surgical ruler, a dissection table, and photographic equipment, and ensured good ventilation. Ensuring good ventilation when working with formalin-conserved tissues is for safety, as formalin is a carcinogenic substance.

Starting from the right knee of a cadaver 1, we first opened the tissue carefully around the knee to give us a clear view into the knee capsule. We were looking at where the genicular arteries originate. As discussed earlier in this thesis, we investigated the anatomy of a knee. The structure we were looking at was the lateral inferior genicular artery, which originates from the popliteal artery.

Figure 3 - 1 Balsamized right knee opened

Figure 3-1 presents a visual of the knee capsule after the skin has been carefully excised. The lateral superior genicular artery arises from the space the arrow is pointing to. The artery is located near the proximal patella and the quadriceps tendon. When it comes to tissue visibility on an embalmed cadaver, finding the artery wasn’t an easy process. Figure 3-2 shows a closer view of where the artery we are looking at arises and how the tissues compare against the surgical measurement scale. The measurement scale is used in the figures above and below, and in subsequent ones, to show the sizes of the structures and to orient us to the correct scale.

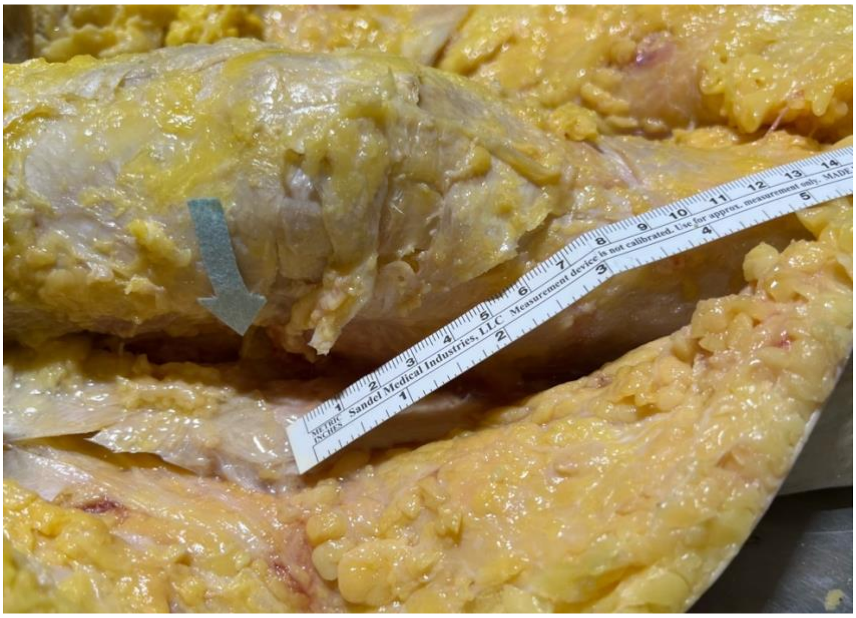

Figure 3 - 2 View and location of the lateral inferior genicular artery

Figure 3-3 shows the size of the structure we are looking for. Without dissecting the knee as much as in the figure, we wouldn't have been able to find it. However, during the dissection, we lost the other end of the artery and due to bad tissue visibility, we couldn't find its continuation.

After the shortcoming, we decided to approach this right knee from the medial side. The medial side was more intact. With tissue visibility still "yellow," we could find the potential medial inferior genicular artery.

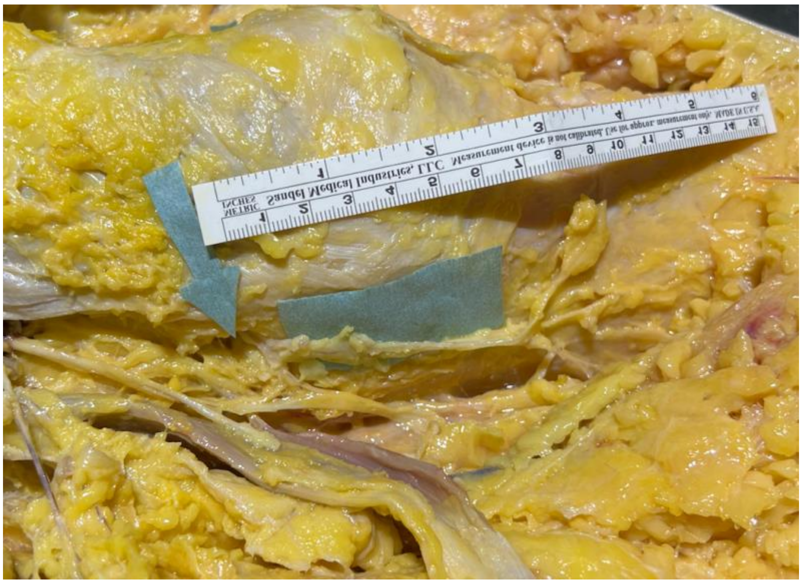

Figure 3 - 3 Medial inferior genicular artery

Figure 3-3 also shows the medial inferior genicular artery of a cadaver 1's right knee from the medial side. The artery is more visible than on the lateral side. Also, its length is good, as measured with a surgical ruler.

Figure 3 - 4 Potential site for anastomose on later steps

Picture of a potential site for anastomosis, as seen in Figure 3-4. The length was measured to be sufficient. In Figures 3-4 and 3-5, the final step of surgery is seen where the vascularized graft was inserted in the ACL place, and the recipient artery (lateral superior genicular artery) was pulled out through the medial knee incision, and the figure shows enough length of the recipient (superior lateral artery) and donor inferior medial artery.

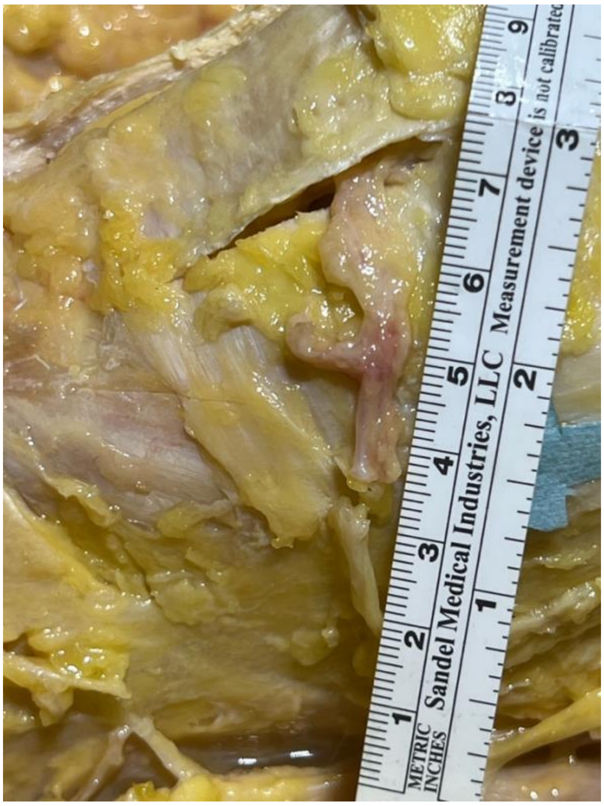

Figure 3 - 5 Closer up the length of planned anastomose place

Not much space for an error. As seen in Figure 3-5. In the figure, you can see the cut patellar ligament as well. Figure 3-5 shows the location of the planned anastomose on later stages of the process + the yellow intracutaneous adipose tissue.

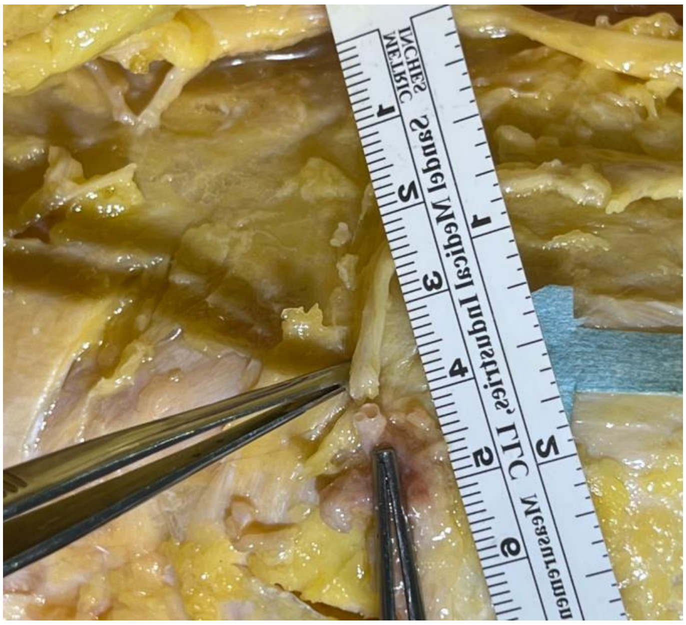

Figure 3 - 6 Size of the artery

The diameters of the vessels can be seen in the figures above (3-6); a diameter of around 1-1,5 mm is observed.

5.2.1. Created graft

In this chapter, I am presenting the created graft.

Figure 4 - 1 Length of graft 1

The length of our graft is around 76 mm, as seen in Figure 4-1.

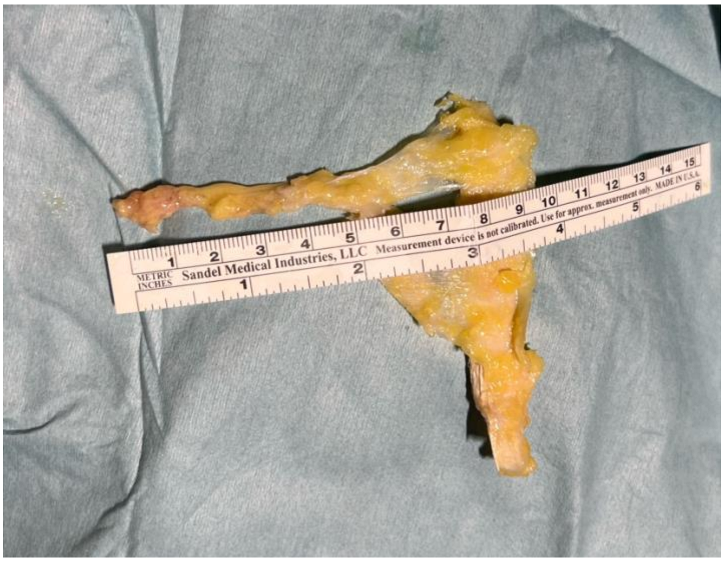

Figure 4 - 2 Width of the created graft

Figure 4-2 shows the width, from the end planned for anastomosis to the lateral side of the ligament. The graft with the recipient (superior lateral genicular artery) and the length of the recipient artery are seen. The soft-tissue piece containing the artery for anastomosis in later stages is located on the left. The width of the grafted ligament, around 1 cm wide piece (origin: patellar ligament). Posterior view of a graft seen on (fill).

Figure 4 - 3 Posterior side of created graft

Posterior side of the created graft is seen in figure 4-3, where the bony part of the patella is seen as well as the bony part of the tibia. Between them is the patellar ligament. Graft wide, around 1 cm wide piece (origin: patellar ligament).

5.2.2. Cadaver 2 – frozen knee

This cadaver provided the best tissue visibility, and the anatomical structures were easily differentiated. We also managed to achieve a perfect graft, which we took to Santaros Klinikos, where we attempted microsurgical anastomoses. Work began by drawing rough schematics on the skin.

Figure 5 - 1 Preparation

In Figure 5-1 above, we can see the drawn patella, ligamentum patellae, collateral ligaments, and possible sources of the lateral and medial inferior genicular arteries.

With the previous dissections, our technique improved, and with the advantages of frozen cadaver, we found the medial inferior genicular artery fast and easily. We marked our structures of interest on top of the fascia lata with a surgical marker.

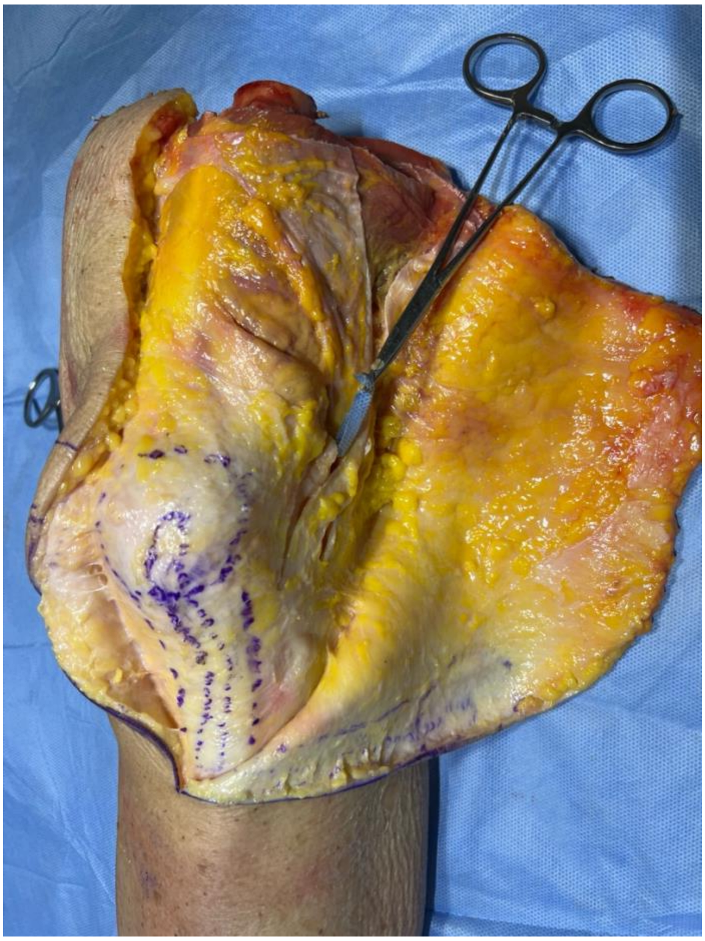

Figure 5 - 2 Locating the medial superior genicular artery

Figure 5-2 shows the drawing of the patellar ligament, and the instrument is near the quadriceps tendon, at the top of the patella. The instrument is holding the medial superior genicular artery so that we don’t lose it during the procedure, as shown in Figure 5-2. Also note the drawing on the patellar ligament. After securing the artery, we could proceed to detach our new ligament from the patellar ligament to create the actual BTB graft.

Figure 5 - 3 Layers of the patellar ligament

In Figure 5-3, the left lateral side of our upcoming graft is cut. Notice the central part of our newly created tendon. With a sharp surgical scalpel, the fascia lata and ligamentum patellaris cut easily, as in figure 5-4.

Figure 5 - 4 Cutting the patellar ligament

Figure 5 - 5 Cut ligament for a graft of the medial inferior genicular artery located

Figure 5-5 presents the created BTB graft with soft tissues around and the dissected recipient lateral superior artery.

To make the final cuts, we used a “Dremel”. In orthopaedic surgery, many power tools can be used as the structures to cut are hard. Also, the chisel was used to lift the bony parts from their places. In Figure 5-6, you can see the process of using Dremel.

Figure 5 - 6 Using Dremel

We used a suture to tie the artery to have a marker to find it later. In Figure 5-7, notice the surgical suture that’s tied to the planned anastomosis site. The figure presents a BTB graft with the lateral superior artery.

Figure 5 - 7 BTB graft with lateral superior artery

Let’s proceed to remove the graft from its place.

Figure 5 - 8 Defect of the patellar ligament after harvesting BTB vascularized graft and dissected donor (superior lateral) artery.

In Figure 5-8, the defect of the patellar ligament after harvesting the BTB vascularized graft and dissecting the donor (superior lateral) artery is seen.

After removing our graft, it is time to close the patellar ligament, as seen in Figure 5-9 and Figure 6-1. Bone cement can be used to fill the small holes left in the patella and tibia from which the graft was taken.

Figure 5 - 9 Sewing the patellar ligament after defect

Figure 6 - 1 Patellar ligament sewn together, defect closed

In the above figures 5-9 and 6-1, the patellar ligament was sutured back together. We used a 4-0 Vicryl suture. After that, we looked for the lateral inferior genicular artery. From the previous dissections, we know that finding it would be harder, but as happened with the medial side, we can now locate it very easily, as seen in Figure 6-2.

Figure 6 - 2 Place for anastomosis after graft

5.2.3. Opening of the knee and insight into the theory of replacement

Here we are trying to put the new graft into the canal we prepared. The boreholes were done (pictures of those stages are not included). In the figures below, pay attention to the canal where the ACL and PCL are located. The PCL is still intact in the canal. As seen in Figure 7-1, 7-2 and 7-3 to make the investigation simpler, we did ACL surgery absolutely non-normal way, the surgery we did was not real open surgery neither arthroscopic surgery; to simplify our work we cut quadriceps tendon and open the knee as a pocket. The task was to insert a ligament on the simplest way, because we wanted to show whether it was possible to insert vascularized graft and it if it would be enough length of recipient artery.

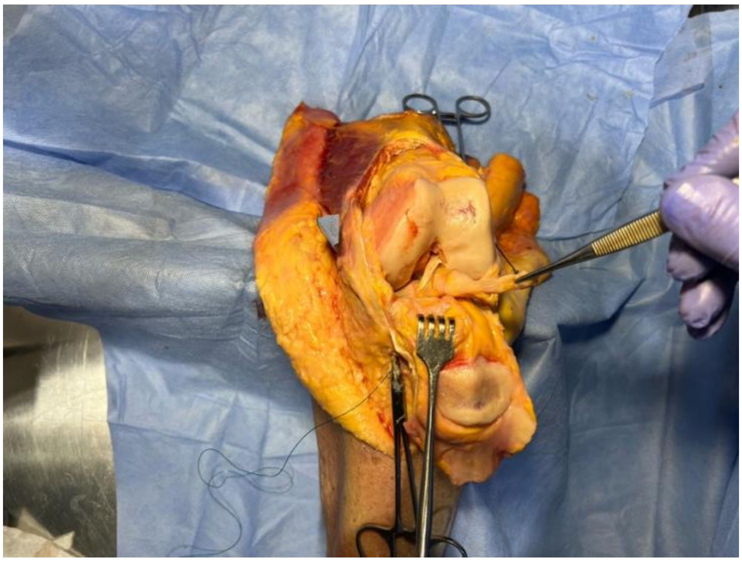

Figure 7 - 1 Dissection of the knee

While the knee was opened and our new graft was inserted in the correct position, we had to ensure the length of the arterial segment was sufficient to reach the inferior genicular artery. As seen in Figure 7-2.

Figure 7 - 2 Length of the arterial segment

The knee was put back together in Figure 7-3.

Figure 7 - 3 Knee put back together

Now let's go back to the medial side of the knee as Figure 7-4 shows.

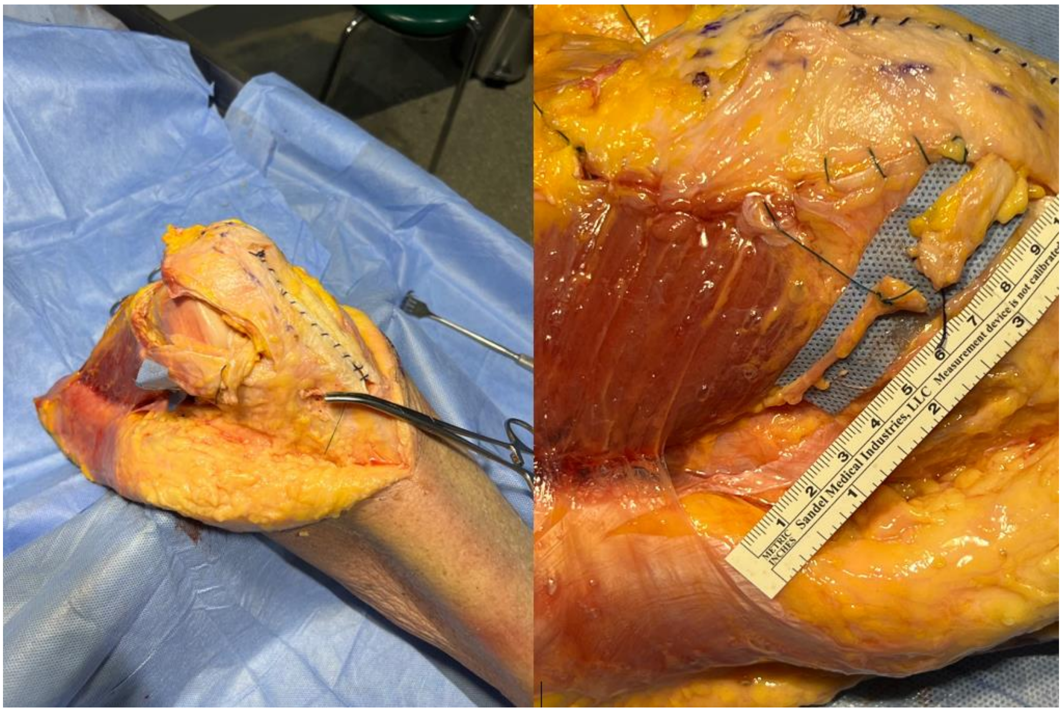

Figure 7 - 4 Closed knee with graft inside

In Figure 7-4, the arterial portion of our graft was left near the medial inferior genicular artery; on the right, the distance seems sufficient for an anastomosis. The operating area of the knee was closed.

5.2.4. Graft from frozen cadaver

In Figure 7-5, the graft taken from a frozen cadaver measured around 9 mm sleave from the femoral end and 9mm sleave for tibial end. Normally, when a patellar tendon graft is inserted, the graft is used upside down (the bone fragment from the tibia goes into the femur, and the bone fragment from the patella goes into the tibia). Normally, the graft is inserted from the tibial tunnel to the femur, with one end smaller than the other.

Bony parts were measured with the metal shell simulating the borehole inside the femur.

Figure 7 - 5 Measurement of the 2nd graft

5.2.5. The practice of anastomoses

Since we had a perfect candidate for a graft, what remained was creating anastomoses in such small arteries. The diameter of the inferior genicular artery is around 1mm. In our setup, we had a surgical microscope, a good lighting source, a preparation pad with needles as tissue holders, millimetre paper, 9-0 Prolene for suturing, and blue contrast paper. In the following figures, you can see sutures placed.

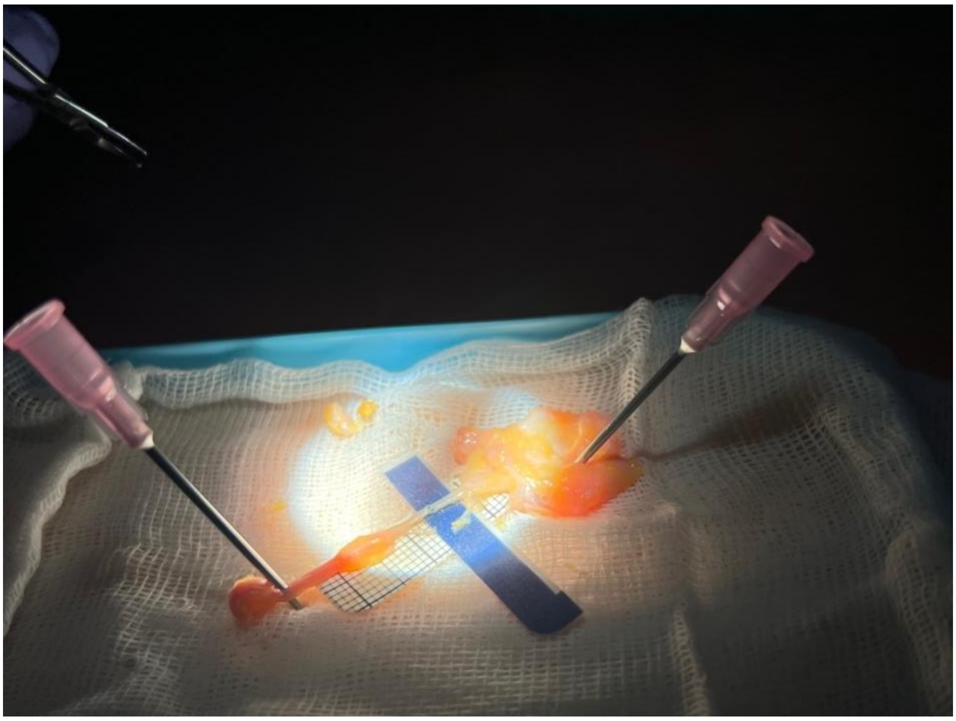

Figure 8 - 1 Microsurgery setup

In Figure 8-1, you can see how the pieces of arteries were set up under the surgical microscope. The setup was perfect to try suturing. The tissue pieces were fixed with 14G needles.

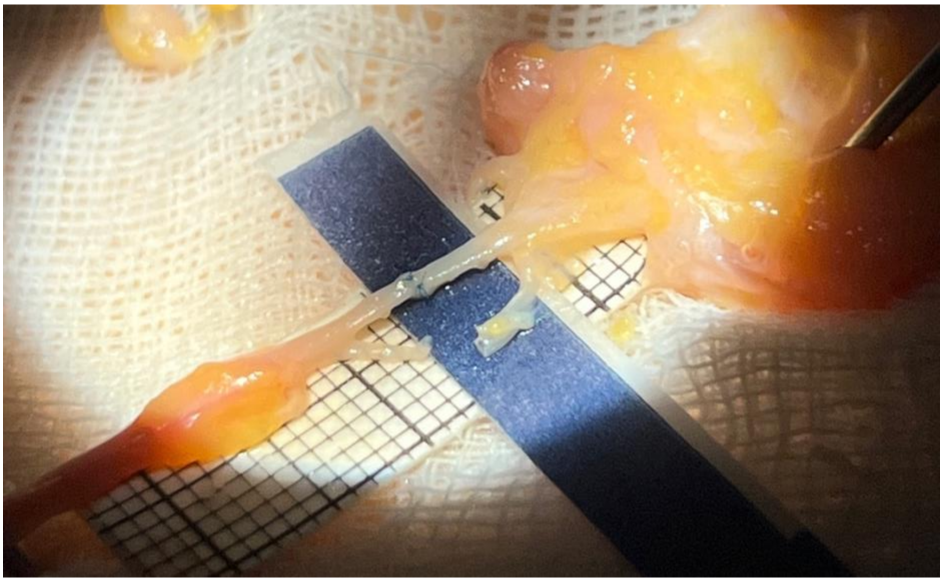

Figure 8 - 2 Closer up anastomose

Closer up the newly created anastomose in Figure 8-2. The prolene suture is blue.

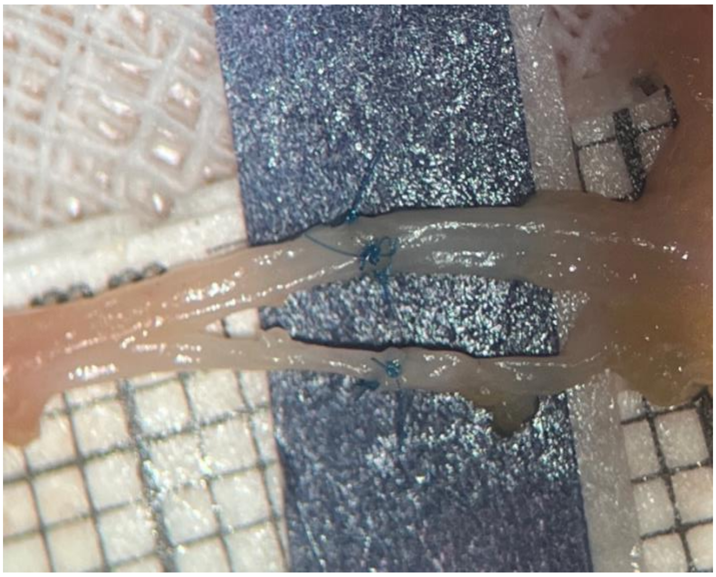

Figure 8 - 3 Artery and vein sewn together

Artery and vein successfully connected – anastomoses in Figure 8-3. The figure is magnified to better illustrate the scale.

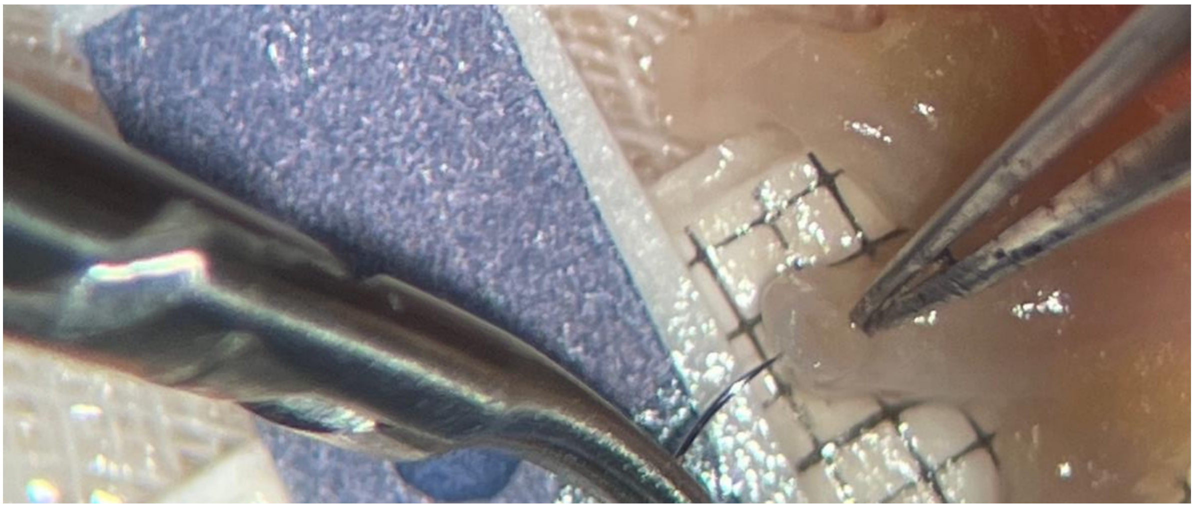

Figure 8 - 4 Rations of microsurgery

The margins were small but with precision we made it possible. As in Figure 8-4 in close the ration can be seen. Each black box is 1 mm to 1mm in size. The surgical instruments are used for sewing.

To summarise all the cadaver works, we couldn't create grafts from the second knee of cadaver 1. Using another knee from cadaver 1 and frozen cadaver 2, we created patellar tendon BPTB graft with the cadaver 2 graft, we were able to take a long enough piece of the lateral genicular artery with the graft, which we tried to put together by sewing the arteries to create an anastomosis under a Leica ™ surgical microscope at the department of reconstructive plastic surgery at Vilnius University's university hospital Santaros Klinikos, where V. Tutkus works. We managed to sew the arteries even though their diameter was around 1 mm, to create an anastomosis. Further cadaveric openings for this thesis were not performed due to the unavailability of the cadavers and because the information sought was successfully collected.

6. Discussion

6.1. Potential advantages of a vascularized graft

Developing a way for high-performance/elite athletes to return to their sports and careers faster than current methods in ACL reconstruction could gain popularity, as it would save substantial financial resources by reducing "off time". As explained earlier, what our method would mean for NHL players, the money around the NHL segment is big, and every game and play counts. By decreasing the "off time" being off hockey ring and exercises the team and the player would save financial resources potentially outweighing high risks associated with it. Secondly, as a new surgical innovation, it could potentially pave the way for new development in the field of microsurgery, and we could see adaptations of our method to be used not just in ACL ligament grafts but with some other ligament grafts needed, or maybe even after the development of artificial ligaments with vasculature.

6.2. Potential disadvantages of vascularized grafts

Gaining access to the knee structures and creating a vascularized graft requires surgical precision and further research to achieve the greatest possible level of minimally invasive surgery. In our current research on creating the vascularized graft, our methods are highly invasive and would not be used in real-life scenarios. The surgery would cause more harm than benefits.

Not just with the actual operation, there are risks, but with the actual graft itself. When tissue is moved from place A to place B in the body, or when an allograft is used, an inflammatory reaction occurs. Even in theory, how vascularized graft could shorten the healing phases, the possibility for inflammation, beforementioned graft healing stages can still occur.

Potential complications of our technique and of vascularized grafts in general include graft-related thrombosis in the vasculature. In the making of vascularized grafts, arterial connections are made through anastomoses, creating potential sites for thrombosis. With the higher risk of thrombosis, the viability of our newly created graft would be compromised. If the anastomoses didn't work, our graft would no longer be a vascularized graft but rather a normal BPTB graft with unnecessary loose tissue that is not supplied with blood. That tissue could develop local inflammation, infection and tissue necrosis, risking the nearby structures, and in the worst case, the inflammation would lead us to amputation of the whole leg or even into systemic infection and in the worst case could be, life-threatening. Also, when live tissues are moved, they heal as a normal wound. The problem is the morbidity of tissues by harvesting arteries and removing paratendon tissues from the patellar ligament. The question remains: Can it harm the patellar ligament?

Given the above-mentioned risks, the risks associated with a vascularized graft are significant and, in the current setting, could potentially outweigh its benefits.

6.3. Current surgical landscape

In the current surgical landscape in orthopaedics and veterinary medicine, I couldn't find case reports of the use of a similar "vascularized" graft as shown. The field of orthopaedics is evolving, so it needs the techniques. By going forward with further research, we could make a way for the new era of surgery - multidisciplinary surgery. The multidisciplinary surgery would combine micro- and orthopaedic surgeries.

Big question: Will there be a need and interest in further developments in ACL reconstruction, or is the current fashion sufficient, with the future potentially centred on QT grafts and hybrid operations?

7. Conclusions

ACL reconstruction has evolved significantly over the years, from the early pioneers of open knee surgery to modern-day arthroscopic techniques. The field of orthopaedics has seen significant innovation and incredible effort in researching new methods. The main goals of ACL reconstruction are restoring full knee joint stability, achieving the fastest, most painless healing and recovery times, and helping patients return to the activities they could do before the injury.

The hamstring tendon-based graft is currently the most used graft type for ACL reconstruction, and the BPTB remains a good option for high-performance/elite athletes. In the future, QT grafts will become more popular, and we may see new adaptations.

Our work on the vascularized graft could open the door to innovation not just in orthopaedics and ACL grafts, but also in other grafts on humans and animals. It is an interesting idea to take advantage of the genicular arteries' vast network. Medicine needs pioneers to test and speculate to innovate, for research to take place. A vascularized graft would be a new, innovative surgical method of its time!

8. The Importance of the Current Master's Thesis

This master's thesis seeks to gather the main ideas and methods for ACL reconstruction and to present a new theoretical graft for use in ACL reconstruction. The information on how ACL reconstruction has developed is scattered, and in the history of medicine, there haven't been successful attempts to create a similar vascularized graft to my knowledge, as presented in the thesis.

8.1. Why the vascularized ligament could be a game changer?

The vascularized graft is an interesting idea of using microsurgery and the patient's own tissue to create, potentially, the fastest healing graft. The benefits of a graft could save valuable healthcare resources and reduce athletes' time off from training and competitions.

Potential for development

- Understanding the vasculature and structures of the knee is essential for the development of new types of graft materials and artificial joints.
- A similar vascularized graft concept could potentially be used on other parts of the body.
- With advances in surgical techniques, the surgical world is increasingly moving toward minimally invasive surgery. Techniques must be researched and streamlined to be safe, cost-effective and usable in real-life scenarios.

Literature

1. Murawski CD, Wolf MR, Araki D, Muller B, Tashman S, Fu FH. Anatomic Anterior Cruciate Ligament Reconstruction: Current Concepts and Future Perspective. CARTILAGE. 2013 Jul;4(3_suppl):27S-37S. doi:10.1177/1947603513486557

2. Scott WN, Insall JN, editors. Insall & Scott surgery of the knee. Phliladelphia, PA: Churchill Livingstone, Elsevier; 20.

3. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH. Anatomic, Radiographic, Biomechanical, and Kinematic Evaluation of the Anterior Cruciate Ligament and Its Two Functional Bundles. J Bone Jt Surg. 2006 Dec;88(suppl_4):2–10. doi:10.2106/JBJS.F.00616

4. Kopf S, Pombo MW, Szczodry M, Irrgang JJ, Fu FH. Size Variability of the Human Anterior Cruciate Ligament Insertion Sites. Am J Sports Med. 2011 Jan;39(1):108–13. doi:10.1177/0363546510377399

5. Somerson JS, Isby IJ, Hagen MS, Kweon CY, Gee AO. The Menstrual Cycle May Affect Anterior Knee Laxity and the Rate of Anterior Cruciate Ligament Rupture: A Systematic Review and Meta-Analysis. JBJS Rev. 2019 Sep;7(9):e2–e2. doi:10.2106/JBJS.RVW.18.00198

6. Csapo R, Juras V, Heinzle B, Trattnig S, Fink C. Compositional MRI of the anterior cruciate ligament of professional alpine ski racers: preliminary report on seasonal changes and load sensitivity. Eur Radiol Exp. 2020 Dec;4(1):64. doi:10.1186/s41747-020-00191-0

7. Du PZ, Markolf KL, Boguszewski DV, McAllister DR. Femoral Contact Forces in the Anterior Cruciate Ligament Deficient Knee: A Robotic Study. Arthroscopy. 2018 Dec;34(12):3226–33. doi:10.1016/j.arthro.2018.06.051

8. Strobel M, Zantop T, Konopatzki H, Strobel M. The anterior cruciate ligament: anatomy, evaluation, operative techniques. Tuttlingen: Endo-Press; 2010. 547 p.

9. Bram JT, Magee LC, Mehta NN, Patel NM, Ganley TJ. Anterior Cruciate Ligament Injury Incidence in Adolescent Athletes: A Systematic Review and Meta-analysis. Am J Sports Med. 2021 Jun;49(7):1962–72. doi:10.1177/0363546520959619

10. Zhi X, Wen Z, Zhang J, Lai D, Ye H, Wu J, et al. Epidemiology and distribution of cruciate ligament injuries in children and adolescents, with an analysis of risk factors for concomitant meniscal tear. Front Pediatr. 2024 Mar 8;12:1332989. doi:10.3389/fped.2024.1332989

11. Castellanos Dolk D, Hedevik H, Stigson H, Wretenberg P, Kvist J, Stålman A. Nationwide incidence of anterior cruciate ligament reconstruction in higher-level athletes in Sweden: a cohort study from the Swedish National Knee Ligament Registry linked to six sports organisations. Br J Sports Med. 2025 Apr;59(7):470–9. doi:10.1136/bjsports-2024-108343

12. Axelrod K, Canastra N, Lemme NJ, Testa EJ, Owens BD. Epidemiology With Video Analysis of Knee Injuries in the Women's National Basketball Association. Orthop J Sports Med. 2022 Sep 1;10(9):23259671221120832. doi:10.1177/23259671221120832

13. Guy S, Fayard JM, Saithna A, Bahroun S, Ferreira A, Carrozzo A, et al. Risk of Graft Rupture After Adding a Lateral Extra-articular Procedure at the Time of ACL Reconstruction: A Retrospective Comparative Study of Elite Alpine Skiers From the French National Team. Am J Sports Med. 2022 May;50(6):1609–17. doi:10.1177/03635465221085027

14. Bayer S, Meredith SJ, Wilson KW, De Sa D, Pauyo T, Byrne K, et al. Knee Morphological Risk Factors for Anterior Cruciate Ligament Injury: A Systematic Review. J Bone Jt Surg. 2020 Apr 15;102(8):703–18. doi:10.2106/JBJS.19.00535

15. Högberg J, Sundberg A, Della Villa F, Hamrin Senorski E. Anterior cruciate ligament injury mechanism in athletes across various sports: a scoping review. Ann Jt. 2025 Oct;10:35–35. doi:10.21037/aoj-25-51

16. Mahapatra P, Horriat S, Anand BS. Anterior cruciate ligament repair – past, present and future. J Exp Orthop. 2018;5(1):20. doi:10.1186/s40634-018-0136-6

17. Sandon A, Werner S, Forssblad M. Factors associated with returning to football after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015 Sep;23(9):2514–21. doi:10.1007/s00167-014-3023-4

18. Thomson J, Webb M. What are the Graft Options for Anterior Cruciate Ligament (ACL) Reconstruction? Orthop Rev. 17:143767. doi:10.52965/001c.143767 PubMed PMID: 40919601; PubMed Central PMCID: PMC12413931.

19. Lin KM, Boyle C, Marom N, Marx RG. Graft Selection in Anterior Cruciate Ligament Reconstruction. Sports Med Arthrosc Rev. 2020 Jun;28(2):41–8. doi:10.1097/JSA.0000000000000265

20. Runer A, Keeling L, Wagala N, Nugraha H, Özbek EA, Hughes JD, et al. Current trends in graft choice for anterior cruciate ligament reconstruction – part I: anatomy, biomechanics, graft incorporation and fixation. J Exp Orthop. 2023 Jan;10(1):37. doi:10.1186/s40634-023-00600-4

21. Pereira VL, Medeiros JV, Nunes GRS, De Oliveira GT, Nicolini AP. Tibial-graft fixation methods on anterior cruciate ligament reconstructions: a literature review. Knee Surg Relat Res. 2021 Dec;33(1):7. doi:10.1186/s43019-021-00089-0

22. Runer A, Keeling L, Wagala N, Nugraha H, Özbek EA, Hughes JD, et al. Current trends in graft choice for anterior cruciate ligament reconstruction – part I: anatomy, biomechanics, graft incorporation and fixation. J Exp Orthop. 2023 Jan;10(1):37. doi:10.1186/s40634-023-00600-4

23. McDermott E, DeFoor MT, Blaber OK, Aman ZS, DePhillipo NN, Dekker TJ. Biomechanical comparison of anterior cruciate ligament reconstruction fixation methods and implications on clinical outcomes. Ann Jt. 2023 Apr;8:15–15. doi:10.21037/aoj-22-52

24. Lubowitz JH, Amhad CH, Anderson K. All-Inside Anterior Cruciate Ligament Graft-Link Technique: Second-Generation, No-Incision Anterior Cruciate Ligament Reconstruction. Arthroscopy. 2011 May;27(5):717–27. doi:10.1016/j.arthro.2011.02.008

25. Gamboa JT, Shin EC, Pathare NP, McGahan PJ, Chen JL. Graft Retensioning Technique Using an Adjustable-Loop Fixation Device in Arthroscopic Anterior Cruciate Ligament Reconstruction. Arthrosc Tech. 2018 Feb;7(2). doi:10.1016/j.eats.2017.08.067

26. Tuca M, Valderrama I, Eriksson K, Tapasvi S. Current trends in anterior cruciate ligament surgery. A worldwide benchmark study. J ISAKOS. 2023 Feb;8(1):2–10. doi:10.1016/j.jisako.2022.08.009

27. Falconiero R, DiStefano V, Cook T. Revascularization and ligamentization of autogenous anterior cruciate ligament grafts in humans. Arthroscopy. 1998 Mar;14(2):197–205. doi:10.1016/S0749-8063(98)70041-6

28. Sim K, Rahardja R, Zhu M, Young SW. Optimal Graft Choice in Athletic Patients with Anterior Cruciate Ligament Injuries: Review and Clinical Insights. Open Access J Sports Med. 2022 Jul;Volume 13:55–67. doi:10.2147/OAJSM.S340702

29. Gharpinde MR, Jaiswal AM, Dhanwani Y. A Comprehensive Review of Graft Choices and Surgical Techniques in Primary Anterior Cruciate Ligament Reconstruction: An Outcome Analysis. Cureus. 2024 Sep 5. doi:10.7759/cureus.68701

30. Arnold MP, Calcei JG, Vogel N, Magnussen RA, Clatworthy M, Spalding T, et al. ACL Study Group survey reveals the evolution of anterior cruciate ligament reconstruction graft choice over the past three decades. Knee Surg Sports Traumatol Arthrosc. 2021 Nov;29(11):3871–6. doi:10.1007/s00167-021-06443-9

31. Min JH, Yoon HK, Oh HC, Youk T, Ha JW, Park SH. Graft choice to decrease the revision rate of anterior cruciate ligament reconstruction: a nationwide retrospective cohort study. Sci Rep. 2024 Aug 28;14(1):20004. doi:10.1038/s41598-024-71068-0

32. Baawa-Ameyaw J, Plastow R, Begum FA, Kayani B, Jeddy H, Haddad F. Current concepts in graft selection for anterior cruciate ligament reconstruction. EFORT Open Rev. 2021 Sep;6(9):808–15. doi:10.1302/2058-5241.6.210023

33. Tuca M, Valderrama I, Eriksson K, Tapasvi S. Current trends in ACL surgery. A worldwide benchmark study. J ISAKOS Jt Disord Orthop Sports Med. 2022 Sep 1. doi:10.1016/j.jisako.2022.08.009

34. Fan D, Ma J, Zhang L. Patellar tendon versus artificial grafts in anterior cruciate ligament reconstruction: a systematic review and meta-analysis. J Orthop Surg. 2021 Dec;16(1):478. doi:10.1186/s13018-021-02624-x

35. Widner M, Dunleavy M, Lynch S. Outcomes Following ACL Reconstruction Based on Graft Type: Are all Grafts Equivalent? Curr Rev Musculoskelet Med. 2019 Dec;12(4):460–5. doi:10.1007/s12178-019-09588-w

36. Mouarbes D, Menetrey J, Marot V, Courtot L, Berard E, Cavaignac E. Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis of Outcomes for Quadriceps Tendon Autograft Versus Bone–Patellar Tendon–Bone and Hamstring-Tendon Autografts. Am J Sports Med. 2019 Dec;47(14):3531–40. doi:10.1177/0363546518825340

37. West RV, Harner CD. Graft Selection in Anterior Cruciate Ligament Reconstruction. JAAOS - J Am Acad Orthop Surg. 2005 Jun;13(3):197.

38. Sciarretta FV. History of anterior cruciate ligament surgery. J Arthrosc Surg Sports Med. 2020 Jun 16;1(1):90–7. doi:10.25259/JASSM_8_2020

39. Kunze KN, Moran J, Polce EM, Pareek A, Strickland SM, Williams RJ. Lower donor site morbidity with hamstring and quadriceps tendon autograft compared with bone-patellar tendon-bone autograft after anterior cruciate ligament reconstruction: a systematic review and network meta-analysis of randomized controlled trials. Knee Surg Sports Traumatol Arthrosc. 2023 Aug;31(8):3339–52. doi:10.1007/s00167-023-07402-2

40. Mistry H, Metcalfe A, Colquitt J, Loveman E, Smith NA, Royle P, et al. Autograft or allograft for reconstruction of anterior cruciate ligament: a health economics perspective. Knee Surg Sports Traumatol Arthrosc. 2019 Jun;27(6):1782–90. doi:10.1007/s00167-019-05436-z

41. Legnani C, Ventura A, Terzaghi C, Borgo E, Albisetti W. Anterior cruciate ligament reconstruction with synthetic grafts. A review of literature. Int Orthop. 2010 Apr;34(4):465–71. doi:10.1007/s00264-010-0963-2

42. Jin H, Tahir N, Jiang S, Mikhail H, Pavel V, Rahmati M, et al. Management of Anterior Cruciate Ligament Injuries in Children and Adolescents: A Systematic Review. Sports Med - Open. 2025 Apr 23;11(1):40. doi:10.1186/s40798-025-00844-7

43. Matsuzaki Y, Chipman DE, Hidalgo Perea S, Green DW. Unique Considerations for the Pediatric Athlete During Rehabilitation and Return to Sport After Anterior Cruciate Ligament Reconstruction. Arthrosc Sports Med Rehabil. 2022 Jan;4(1). doi:10.1016/j.asmr.2021.09.037

44. Tashman S, Zandiyeh P, Irrgang JJ, Musahl V, West RV, Shah N, et al. Anatomic single- and double-bundle ACL reconstruction both restore dynamic knee function: a randomized clinical trial—part II: knee kinematics. Knee Surg Sports Traumatol Arthrosc. 2021 Aug;29(8):2676–83. doi:10.1007/s00167-021-06479-x

45. DeFrate LE. Effects of ACL graft placement on in vivo knee function and cartilage thickness distributions: IN VIVO ACL GRAFT PLACEMENT. J Orthop Res. 2017 Jun;35(6):1160–70. doi:10.1002/jor.23541

46. Lind M, Nielsen TG, Soerensen OG, Mygind-Klavsen B, Faunø P. Quadriceps tendon grafts does not cause patients to have inferior subjective outcome after anterior cruciate ligament (ACL) reconstruction than do hamstring grafts: a 2-year prospective randomised controlled trial. Br J Sports Med. 2020 Feb;54(3):183–7. doi:10.1136/bjsports-2019-101000

47. Edwin Smith papyrus | Medical Text, Surgery, Significance, & Location | Britannica [Internet]. [cited 2026 Apr 12]. Available from: https://www.britannica.com/topic/Edwin-Smith-papyrus

48. Davarinos N, O'Neill BJ, Curtin W. A Brief History of Anterior Cruciate Ligament Reconstruction. Adv Orthop Surg. 2014 Apr 17;2014:1–6. doi:10.1155/2014/706042

49. Biographisches Lexikon hervorragender Ärzte des neunzehnten Jahrhunderts [Internet]. Berlin, Wien; 1901. Available from: http://www.zeno.org/nid/2000803494X

50. Yao S, Fu BSC, Yung PSH. Graft healing after anterior cruciate ligament reconstruction (ACLR). Asia-Pac J Sports Med Arthrosc Rehabil Technol. 2021 Jul;25:8–15. doi:10.1016/j.asmart.2021.03.003 PubMed PMID: 34094881; PubMed Central PMCID: PMC8134949.

Origins of figures

Figures 1-1 to 1-5.

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Figure 1-6.

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Figure 1-7.

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Figures 1-8 to 1-10.

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Figure 2-1.

Reproduced from Chhabra A. et al. publication “Anatomic, Radiographic,Biomechanical and Kinematic Evaluation of the Anterior Cruciate Ligament and Its Two Functional Bundles” (3).

Figures 3-1 to 3-6.

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4-1 to 4-3.

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5-1 to 5-9.

Taken by the author.

Fig 6-1 and 6-2.

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Fig 7-1 to 7-5.

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Fig 8-1 to 8-4.

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