



QUALITY IN SPORT

eISSN 2450-3118 · Open Access · Peer-reviewed

apcz.umk.pl/QS
Toruń

Nicolaus Copernicus University in



Cite as: TOMICKA, Ewa, CZAPIŃSKI, Olgierd, ZIĘBA, Natalia, CIESIELSKI, Maciej, KUŚ, Justyna, PYSIEWICZ, Mateusz, BIAŁOWAŚ, Patrycja, KNAPIK, Anna and BRODOWSKA, Anna. Anterior cruciate ligament rupture - exploring mechanism of healing and its impact in different treatment methods. *Quality in Sport*. 2026;57:72398. <https://doi.org/10.12775/QS.2026.57.72398>

ARTICLE TIMELINE

Received: 22.05.2026 Revised: 25.05.2026

Accepted: 31.05.2026 Published: 16.06.2026

INDEXING & EVALUATION

MEiN points: 20 Unique ID: 201398

Disciplines: Medical Sciences; Health Sciences

The journal has been awarded 20 points in the parametric evaluation by the Polish Ministry of Higher Education and Science (Annex to the announcement of 05.01.2024, No. 32553). Unique Journal Identifier: 201398. Scientific disciplines: Medical Sciences; Health Sciences.

Punkty Ministerialne z 2019 – aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Nauki medyczne; Nauki o zdrowiu. © The Authors 2026.

OPEN ACCESS · CC BY-NC-SA 4.0 This article is published with open access under the License Open Journal Systems of Nicolaus Copernicus University in Toruń, Poland, and is distributed under the terms of the Creative Commons Attribution Non-commercial Share Alike License (<http://creativecommons.org/licenses/by-nc-sa/4.0/>), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the work is properly cited. The authors declare no conflict of interest regarding the publication of this paper.

Anterior cruciate ligament rupture - exploring mechanism of healing and its impact in different treatment methods

Authors:

Ewa Tomicka

ORCID: <https://orcid.org/0000-0001-6492-4729>

Non-public Health Care Facility “Lecznica MEDEA”

Warsaw, Poland

ewa.tomicka@vp.pl

Olgierd Czapiński

ORCID: <https://orcid.org/0009-0007-7894-7201>

Institute of Dentistry of the Central Clinical Hospital of the Medical University of Lodz, ul. Pomorska 251, 92-213 Łódź, Poland

olgierd.czapinski@gmail.com

Natalia Zięba

ORCID: <https://orcid.org/0009-0005-4554-9536>

Medical University of Lublin,

Lublin, Poland

natalia.zieba03@gmail.com

Maciej Ciesielski

ORCID: <https://orcid.org/0009-0002-4191-3474>

Medical University of Lodz

Lodz, Poland

maciejciesielski58@gmail.com

Justyna Kuś

ORCID: <https://orcid.org/0009-0006-5562-8702>

Medical University of Lodz

Lodz, Poland

k.justynna@gmail.com

Mateusz Pysiewicz

ORCID: <https://orcid.org/0009-0007-0094-2857>

Norbert Barlicki Memorial Teaching Hospital No. 1

Stefana Kopcińskiego 22 St., 90-153 Łódź, Poland

dreo@outlook.com

Patrycja Białowąs

ORCID: <https://orcid.org/0000-0002-8913-3656>

Andrzej Frycz Modrzewski University, Kraków, Poland

bialowaspatrycja@gmail.com

Anna Knapik

ORCID: <https://orcid.org/0000-0002-9556-7514>

Medical University of Silesia in Katowice

St. Poniatowskiego 14, 40-055 Katowice

aknapik14@gmail.com

Anna Brodowska

ORCID: <https://orcid.org/0009-0008-9227-2869>

Medical University of Lublin,

Al. Raławickie 1

20-059 Lublin, Poland

annabrodowska2001@gmail.com

Abstract

Anterior cruciate ligament (ACL) is one of the primary stabilizers of the knee joint, preventing anterior tibial translation and contributing to rotational stability. ACL rupture is among the most common injuries in young athletes, although it may occur in individuals of any age. In recent years, the incidence of ACL injuries has increased due to greater participation in sports and physically active lifestyles, leading to growing demand for effective treatment methods.

Currently, anterior cruciate ligament reconstruction (ACLR) is considered the standard treatment approach. The procedure typically uses autografts harvested from the patient's own tendons, although allografts and synthetic ligaments may also be utilized. Advances in the understanding of ligament biology and healing mechanisms have contributed to the development of newer primary repair techniques aimed at preserving native ACL tissue and proprioceptive function while reducing donor-site morbidity and enabling earlier rehabilitation.

Although ACLR has been extensively studied and refined over decades, newer repair methods still require further long-term clinical evaluation. Each treatment strategy presents specific advantages and limitations, and none completely eliminates the risk of graft failure or post-traumatic osteoarthritis. This review summarizes the biological phases of ACL healing and discusses current treatment options in relation to these processes.

Keywords: ACL; ligamentization; ACL rupture; ACL reconstruction; ACL repair; allografts; synthetic ligaments

I. Background

With increasing awareness of the benefits of physical activity and improved access to sports, there has been a noticeable rise not only in the number of individuals engaging in exercise but also in the incidence of sports-related injuries. Among these, rupture of the anterior cruciate ligament (ACL) is one of the most common and clinically significant injuries. As the ACL plays a vital role in maintaining the stability and dynamic function of the knee joint, its damage often leads to substantial impairments, including joint pain, restricted range of motion, and the characteristic sensation of the knee "giving way."

Over the years, a substantial number of research has emerged concerning ACL anatomy, biomechanics, mechanisms of injury, and healing processes, as well as various approaches to rupture management. Despite all this knowledge and advances in surgical techniques, optimal treatment strategies remain a topic of ongoing debate. This paper aims to review the major healing processes and their phases associated with ACL rupture to critically evaluate current treatment methods, highlighting their respective advantages and limitations.

II. Methodology

Search Strategy

A literature review was conducted using databases such as PubMed, Google Scholar, and Wiley Online Library. The review covered publications from 1992 to May 2026. The search included a combination of keywords such as: “ACL,” “ACL rupture,” “ACL repair,” “treatment,” “ligamentization” “ACL rupture”, “ACL reconstruction”, “ACL repair”, “allografts”, “synthetic ligaments”, and “histological.”

Inclusion/Exclusion Criteria

Articles included in this literature review had to meet the following criteria: human-based studies, access to full text, inclusion of ACL rupture cases in studies, case-control studies, and the article written entirely in English.

Study Selection

A manual review of the article list obtained using the search strategy was conducted. Based on the inclusion and exclusion criteria, the articles were assessed for their relevance. Full texts of the selected articles were then thoroughly reviewed and analyzed for common patterns and findings.

III. ACL: anatomy, structure and function

The ACL is a key structure located within the knee joint capsule. It originates from the anterior intercondylar area of the tibia, posterior to the anterior attachment of the medial meniscus, and extends superiorly, posteriorly, and laterally. It then inserts onto the posterior part of the medial surface of the lateral femoral condyle. The ACL serves as one of the four primary stabilizing ligaments of the knee joint, alongside the medial collateral ligament (MCL), lateral collateral ligament (LCL), and posterior cruciate ligament (PCL). Together with the PCL, the ACL lies within the joint capsule, forming a cross-like (cruciate)

configuration. Despite being intracapsular, both the ACL and PCL are enclosed within their own synovial membranes and epiligament (EL) mostly consisting of vascular vessels and connective tissue[1, 2, 3].

The primary function of the ACL is to restrain anterior translation of the tibia relative to the femur and to limit internal tibial rotation. It provides approximately 85–87% of the restraining force against anterior tibial translation, depending on the degree of knee flexion. In addition, the ACL works synergistically with the PCL to contribute to joint stability and to protect the articular cartilage and menisci from excessive mechanical stress [4].

From a histological perspective, the ACL consists predominantly of type I collagen (approximately 90%) and type III collagen (approximately 10%). It is organized into two functional bundles: the larger anteromedial (AM) bundle and the smaller posterolateral (PL) bundle. The AM bundle plays a greater role in resisting forces during knee flexion, whereas the PL bundle is more active during extension. In some cases, a third intermediate bundle has been described, located between the AM and PL bundles [2, 5, 6].

The ACL typically measures approximately 27–38 mm in length and 10–12 mm in width, while the AM and PL bundles measure approximately 6–7 mm and 5–6 mm in width, respectively. However, these dimensions vary depending on the degree of knee flexion at the time of measurement [6].

Additionally, collagen fibers within the bundles differ in both size and orientation. While some fibers run transversely, the majority are oriented obliquely to the long axis of the ACL and often follow a spiral pattern. This structural organization enhances the ligament's ability to resist multidirectional stresses during dynamic activities. Moreover, the ACL contains elastin and oxytalan fibers, as well as a parenchyma rich in fibroblasts and mechanoreceptors, contributing to its viscoelastic properties and proprioceptive function [4, 5].

IV. ACL rupture: mechanism and risk factors

ACL tears occur most commonly in athletes, although they are also prevalent among recreationally active individuals. The majority of injuries result from non-contact mechanisms, typically involving a pivoting movement in which the tibia translates anteriorly relative to the femur while the knee is slightly flexed and positioned in valgus alignment. This combination

of anterior shear force and rotational loading places substantial stress on the ACL and is considered the primary mechanism of injury. In contrast, contact mechanisms - such as a direct blow to the lateral aspect of the knee - are less common but still clinically relevant [7, 8].

Sports most frequently associated with ACL injuries are those that involve rapid changes of direction, pivoting, or jumping, including football, basketball, and skiing. More recently, with the increasing popularity of activities such as climbing, a rise in injuries related to falls has also been observed. Epidemiological data suggest that approximately 70–80% of ACL injuries occur through non-contact mechanisms, highlighting the importance of neuromuscular control and movement biomechanics in both injury causation and prevention [8, 9].

Clinical symptoms following ACL rupture typically include acute pain and rapid onset of joint swelling due to hemarthrosis. Many patients report hearing or feeling a characteristic “pop” at the moment of injury. Hemarthrosis contributes to reduced range of motion, while functional instability often presents as the sensation of the knee “giving way.” Several clinical tests are commonly used to assess ACL integrity, including the Lachman test, anterior drawer test, and pivot shift test. Among these, the Lachman test is considered the most sensitive in the acute setting. However, magnetic resonance imaging (MRI) remains the primary non-invasive modality for confirming ACL rupture and assessing associated injuries [9, 10].

Due to the stabilizing role of the ACL and PCL, ACL ruptures are frequently associated with damage to other intra-articular structures, particularly the menisci and articular cartilage. The rotational component of the injury mechanism predisposes to damage of the medial meniscus (MM) more often than to the lateral meniscus (LM), especially in chronic instability. Meniscal tears can be classified into several common types, including radial, longitudinal, horizontal, bucket-handle, flap, and complex tears and they can also influence later choice of treatment. In addition, MRI frequently reveals bone marrow oedema, commonly referred to as “bone bruising,” which reflects the impact forces sustained during injury. Extra-capsular structures such as the MCL and LCL may also be involved, with MCL injuries occurring more frequently in combination with ACL tears due to common valgus position of the knee during the incidence [7, 8, 9, 11, 12].

Risk Factors

Over decades of research, numerous risk factors for ACL rupture have been identified. One of the most consistently reported is sex-related difference, with females demonstrating a significantly higher risk compared to males. Reported female-to-male ratios range from approximately 2.7:1 to 4.5:1. This disparity is thought to arise from a combination of anatomical, biomechanical, and neuromuscular factors. For example, female athletes often exhibit altered movement patterns, such as increased knee valgus angles and reduced knee and hip flexion during landing and cutting manoeuvres, which increase strain on the ACL [10, 13, 14]. Additionally, differences in quadriceps-to-hamstring strength ratios and neuromuscular control may contribute to decreased dynamic stabilization of the knee joint [8, 10, 11, 13].

Joint laxity and generalized hypermobility have also been implicated as contributing factors, particularly in female populations. The influence of hormonal factors remains an area of ongoing investigation. Although there is no clear consensus, several studies suggest that the risk of ACL injury may be higher during the follicular or preovulatory phase of the menstrual cycle. During these phases, elevated oestrogen levels may reduce ligament stiffness and increase laxity. Furthermore, relaxin - a hormone which production is stimulated by oestrogen - has been shown to bind to ligamentous tissue, promoting degradation of type I collagen, the primary structural component of the ACL. Relaxin also stimulates the production of matrix metalloproteinases, which further contribute to ligament weakening. Some evidence suggests that women using oral contraceptive pills (OCPs) may have lower circulating relaxin levels, potentially offering a protective effect; however, the relationship between hormonal factors and ACL injury risk remains inconclusive and requires further investigation [8, 15].

ACL rupture can occur across all age groups, but it is most frequently observed in individuals between 16 and 30 years of age, reflecting peak levels of sports participation. This high level of activity is also associated with an increased risk of re-injury. However, with a growing proportion of individuals over 40 years of age maintaining active lifestyle, the incidence of ACL tears in this population is also increasing. In older patients, concomitant injuries - particularly involving the posterior horn of the medial meniscus - are more commonly observed [11, 16]. Additionally, fatigue and imbalances in quadriceps and hamstring muscle strength have been identified as modifiable risk factors, as they can impair neuromuscular

control and increase susceptibility to injury [17]. Other recognized risk factors include anatomical variations such as a narrow intercondylar notch, increased posterior tibial slope, and poor neuromuscular coordination.

V. Diagnosis

Arthroscopy is considered the gold standard for the definitive diagnosis of ACL rupture, as it allows direct visualization of intra-articular structures. However, magnetic resonance imaging (MRI) plays a crucial role in the initial, non-invasive assessment of suspected ACL injuries. MRI not only confirms the presence of a tear but also provides detailed information regarding associated injuries to menisci, cartilage, and surrounding structures [18, 19, 20].

ACL tears can be classified as partial or complete ruptures. Partial tears are characterized by preservation of some ligament fibres and carry a risk of progression to complete rupture, particularly in physically active individuals. However, there is no universally accepted definition of a partial tear, and its diagnosis often depends on a combination of imaging findings and clinical assessment [18, 19].

Based on the location of the tear, the Sherman classification is commonly used to categorize complete ACL ruptures into five types: proximal avulsion (Type I, with >90% of ligament length preserved distally), proximal tear (Type II, 75–90%), midsubstance tear (Type III, 25–75%), distal tear (Type IV, 10–25%), and distal avulsion (Type V, <10%). This classification is clinically relevant, as it may help guide treatment decisions, particularly in determining the feasibility of ACL repair versus reconstruction [20, 21, 22].

VI. ACL healing – mechanism and spontaneous healing

After an injury, a healing process is initiated. Extra-articular ligaments typically heal through three overlapping phases: inflammation, proliferation, and remodelling, ultimately resulting in scar tissue formation. However, the anterior cruciate ligament (ACL), due to its intra-articular location and exposure to synovial fluid, demonstrates a distinct healing response. Four phases are often described: an inflammatory phase, epiligamentous reparative phase, proliferative phase, and remodelling phase [23]. These processes involve synovial lining activation,

neovascularization, inflammatory cell infiltration, as well as structural changes such as hyalinization and calcification, alongside myofibroblast proliferation [23].

The primary natural response to ACL injury is inflammation, triggered by exposure of subsynovial tissues following ligament rupture. Clinically, this is characterized by the classical signs of inflammation: increased temperature (*calor*), redness (*rubor*), pain (*dolour*), swelling (*tumor*), and impaired function (*functio laesa*). The joint often presents with hemarthrosis due to vascular disruption. A cascade of cytokines and growth factors is released, including interleukins and tumour necrosis factor-alpha, which increase vascular permeability and facilitate immune cell migration to the injury site. These processes are essential for clearing cellular debris and initiating tissue repair [23, 24].

The epiligamentous reparative and proliferative phases occur concurrently as the torn ends of the ACL attempt to heal. The epiligament, a connective tissue layer surrounding the ACL, contains a high density of fibroblasts. These cells proliferate and synthesize extracellular matrix components, particularly type I and type III collagen, as well as matrix metalloproteinases that regulate tissue remodelling. However, the intra-articular environment presents a major limitation to healing. Synovial fluid inhibits the formation of a stable fibrin-platelet clot, which normally serves as a scaffold for cell migration and collagen deposition in extra-articular ligaments. Angiogenesis plays a critical role during this stage, as revascularization is necessary for nutrient delivery and cellular activity. Despite the relatively poor vascular supply of the ACL, neovascularization is essential not only for tissue repair but also for reinnervation, which contributes to the restoration of proprioceptive function [23, 24, 25]. Emerging evidence also suggests that biological augmentation strategies, such as platelet-rich plasma (PRP) injection, may enhance this phase by promoting a more favourable healing environment.

The final phase is remodelling, during which the initially formed scar tissue undergoes structural and functional adaptation. The ACL stumps can connect or remain separated. In each situation the ligament adjusts to new joint motion. Collagen fibres become more organized and aligned along the direction of mechanical stress, improving the tensile properties of the tissue. Mechanical loading through rehabilitation exercises is crucial in this phase, as it stimulates ligament adaptation and enhances functional recovery. This process also contributes to the restoration of proprioception and joint stability. Importantly, neurophysiological adaptations occur at the level of the central nervous system, including

changes in motor control, reflex pathways, and muscle activation patterns, which are essential for full functional recovery [26].

Spontaneous healing of the ACL remains a subject of ongoing debate. It has been hypothesized that partial tears may have a greater capacity for healing, as preserved fibres can act as a structural scaffold while maintaining some degree of vascular and neural supply. Clinical and imaging studies suggest that certain factors increase the likelihood of spontaneous healing, including proximal (femoral-sided) single-bundle tears (as proximal attachment have more blood vessel), reduced posterior tibial slope, and limited anterior tibial translation (more physiological bones alignment), all of which contribute to greater joint stability [26, 27]. However, complete tear in some cases can also heal, but the number are varying from 14% of patients up to 53% of patients. [27, 28]. True rate is hard to estimate because ACL is usually evaluated in patients at different time points after the injury. There is also lack of studies with control group as the surgery is usually preferable treatment. Nevertheless, one of the non-surgical treatment called “Cross Bracing Protocol” seem to have promising results. According to it, the knee is immobilized at 90° of flexion for 4 weeks and gradually increased until 12 weeks when the brace is removed [29]. This positioning creates less space between femur and tibia, which makes it easier for the ACL to heal.

VII. ACL rupture treatment methods

Knee joint instability following ACL rupture predisposes patients to secondary injuries involving the joint structures, particularly the medial meniscus (MM) and articular cartilage. In the long term, these injuries may lead to the earlier development of osteoarthritis, resulting in pain, reduced mobility, and decreased quality of life, especially in younger and physically active individuals [30, 31]. Therefore, the aim of treatment is not only to restore mechanical knee stability, but also to enable return to daily activities and sports participation while optimizing long-term functional outcomes and quality of life [32, 33]. Over the years, several surgical approaches have been developed to restore ACL function. The main treatment methods include ACL reconstruction (ACLR) using autografts or allografts, as well as primary ACL repair techniques focused on restoring the continuity of the native ligament.

ACL Reconstruction with autograft

Anterior Cruciate Ligament Reconstruction (ACLR) is currently considered the standard surgical treatment for ACL rupture and is widely performed, particularly in the United States and European countries [32]. The procedure involves harvesting a tendon graft from the patient, preparing it to resemble the native ACL, and securing it between the femur and tibia using fixation devices such as screws or cortical buttons. Numerous surgical techniques exist to achieve graft stability, depending on surgeon preference, graft type, and patient-specific factors.

ACLR is associated with relatively low failure rates, where failure is typically defined as graft re-rupture or persistent postoperative knee instability [33]. Due to the braided structure of tendon grafts, their initial tensile strength may exceed that of the native ACL. However, the biomechanical properties of the graft change considerably during the maturation process [34].

The three most commonly used autografts are Bone–Patellar Tendon–Bone (BPTB) autograft, often regarded as the “gold standard” because of its strong bone fixation and favourable long-term stability, Hamstring Tendon (HT) autograft, usually utilizing the semitendinosus and gracilis tendons braided into multiple strands, most commonly four, and Quadriceps Tendon (QT) autograft, which can vary in thickness and graft preparation technique [5, 35, 36, 37].

The advantages and disadvantages of these grafts are summarized in Table 1. Less commonly used graft sources include the Tensor Fasciae Latae, Achilles tendon, and Peroneus Longus tendon autografts [38]. Allografts may also be used, particularly in revision surgeries or in patients wishing to avoid donor-site morbidity; however, they are associated with slower incorporation and, in some studies, higher failure rates in young active populations [39, 40, 41].

Table 1. Strengths and Weaknesses of each autograft type

	Strengths	Weaknesses
Bone–Patellar Tendon–Bone Autograft (BPTB)	<p>Bone-to-bone healing enables faster graft integration within bone tunnels</p> <p>High initial fixation strength and stiffness, often comparable to or exceeding the native ACL</p> <p>Lower rates of anterior knee laxity postoperatively</p> <p>Reduced risk of graft failure and re-rupture in high-demand patients</p> <p>High return-to-sport rates ($\approx 70\%$ return to pre-injury level)</p>	<p>Donor-site morbidity, including anterior knee pain and pain during kneeling</p> <p>Potential long-term quadriceps weakness</p> <p>Risk of complications such as patellar fracture, patellar tendinopathy, or tendon rupture</p> <p>Increased incidence of patellofemoral osteoarthritis in long-term follow-up</p> <p>Limited use in paediatric patients due to risk of growth plate injury</p>
Hamstring Tendon Autograft (HT)	<p>Lower incidence of anterior knee pain and kneeling discomfort compared to BPTB</p> <p>Preservation of the extensor mechanism</p> <p>High tensile strength, particularly with quadrupled graft constructs</p> <p>Smaller surgical incision and improved cosmetic outcome</p> <p>Lower risk of patellar-related complications</p>	<p>Slower graft incorporation due to tendon-to-bone healing</p> <p>Potential for persistent hamstring weakness, particularly in knee flexion</p> <p>Morphological changes such as muscle atrophy, fatty infiltration, and tendon retraction</p> <p>Slightly increased anterior laxity compared to BPTB in some studies</p>
Quadriceps Tendon autograft (QT)	<p>Larger graft diameter, which may reduce risk of graft failure</p> <p>Lower donor-site morbidity compared to BPTB – lower risk of injury to the infra-patellar branch of the saphenous nerve and lower risk of intra-patellar scarring as patella is not used</p> <p>Reduced risk of anterior knee pain relative to patellar tendon harvest</p> <p>Can be harvested with or without a bone block, allowing surgical flexibility</p> <p>Increasing evidence supports comparable clinical outcomes to BPTB and HT</p>	<p>Lower incidence of anterior knee pain</p> <p>Limited long-term outcome data compared to BPTB and HT</p> <p>Potential donor-site morbidity, including quadriceps weakness</p> <p>Technically more demanding harvesting procedure</p> <p>Risk of postoperative quadriceps inhibition or delayed recovery of strength</p>

Although ACL reconstruction may appear to provide an immediate mechanical solution, graft healing and remodelling is a prolonged biological process. Following fixation, the tendon graft undergoes ligamentization, a transformation process during which the graft gradually acquires characteristics resembling those of the native ACL. This process typically lasts 1–2 years and consists of several overlapping phases [42].

During the first 4 weeks after surgery, an early necrotic phase occurs because the tendon tissue is not naturally adapted to the intra-articular environment. Native tendon cells undergo apoptosis and are progressively replaced by fibroblasts and mesenchymal stem cells migrating from the bone tunnels. Simultaneously, collagen fibres begin to reorganize, resulting in a temporary decrease in the mechanical properties of the graft [43].

Between approximately 4 and 12 weeks postoperatively, the proliferative phase takes place, characterized by intense revascularization and cellular proliferation. During this stage, collagen remodelling becomes more pronounced, and large-diameter collagen fibrils are gradually formed. Despite these changes, the graft is considered biomechanically weakest during this period, making it particularly susceptible to re-rupture [43]. Appropriate rehabilitation and controlled joint motion are therefore essential, as they stimulate synovial fluid circulation, improve vascular supply, and promote tissue remodelling [18].

The final stage is the ligamentization phase, during which vascularity decreases and collagen fibre orientation gradually begins to resemble that of the native ACL. Nevertheless, the graft never fully reproduces the complex ultrastructure and variability of fibre diameters observed in an intact ligament. There is no clearly defined endpoint of ligamentization, although most studies suggest that substantial remodelling continues for at least one year following surgery [43].

ACL Repair

In recent years, ACL repair techniques have gained increasing popularity due to the growing emphasis on minimally invasive and tissue-preserving surgical procedures [44, 45, 46, 47]. Unlike reconstruction, ACL repair aims to preserve the native ligament tissue, including its proprioceptive nerve fibres, while avoiding graft harvesting and graft-related complications such as donor-site morbidity, muscle weakness, or anterior knee pain.

ACL repair is chosen as preferable treatment most often in case of proximal ACL ruptures classified as Sherman type I or II tears, as these injuries possess greater healing potential due

to preservation of vascular and neural structures within the ligament stump [45, 46]. The biological healing process following repair resembles spontaneous ACL healing.

The three principal ACL repair techniques include Dynamic Intraligamentary Stabilization (DIS), Bridge-Enhanced ACL Repair (BEAR), Internal Brace Ligament Augmentation (IBLA).

Because these techniques are relatively new and require specialized surgical equipment, further long-term comparative studies are still needed to evaluate their effectiveness relative to ACL reconstruction. Early evidence suggests that ACL repair may allow faster recovery and earlier return to sport due to preservation of native tissue and less invasive surgical trauma. However, several studies indicate that ACLR may still demonstrate lower re-rupture rates because tendon grafts may provide greater mechanical strength than a healed native ligament [45].

Dynamic Intraligamentary Stabilization (DIS) aims to maintain close approximation of the torn ACL ends to create optimal healing conditions. A spring-based stabilization device is inserted into a tibial tunnel, while a polyethylene cord is passed through the ACL remnants to maintain ligament stump contact during healing. The spring mechanism continuously counteracts anterior tibial translation caused by ACL deficiency while maintaining consistent tension throughout knee motion [46]. This dynamic stabilization may support biological healing and facilitate earlier rehabilitation and return to sport. In selected cases, the implant may later be removed.

Bridge-Enhanced ACL Repair (BEAR) was developed to biologically stimulate healing between the torn ends of the ACL by creating a scaffold within the rupture gap. The implant, typically composed of bovine collagen, is saturated with the patient's autologous blood before implantation. Since synovial fluid inhibits spontaneous clot formation within the ACL, the collagen scaffold enriched with blood provides cytokines, platelets, and growth factors that promote tissue healing [47]. Over time, the scaffold becomes infiltrated by host cells and is gradually resorbed while newly formed collagen tissue develops. This process generally occurs within approximately 8 weeks following surgery and allows early initiation of rehabilitation.

Internal Brace Ligament Augmentation (IBLA) involves suturing the torn ACL remnants together and reinforcing them with high-strength suture tape. The tape functions as a

secondary stabilizer that protects the healing ligament during early mobilization and rehabilitation [48]. By sharing mechanical loads with the healing tissue, IBLA may reduce stress on the repaired ACL while preserving native ligament structures and proprioceptive function.

Allografts

Another option for ACL reconstruction is the use of allografts. These grafts are typically obtained from cadaveric donors and most commonly include patellar tendon, hamstring tendon, Achilles tendon, and tibialis tendon grafts [36]. The harvesting and preparation techniques are similar to those used for autografts; however, allografts allow for the excision of longer tissue segments without donor-site morbidity in the recipient.

Despite these advantages, several important limitations must be considered. Differences in graft size between donor and recipient may create challenges in graft matching. Tissue banks help address this issue by storing and processing donor grafts, although legal regulations regarding tissue banking vary between countries. Additional concerns include the potential transmission of infectious diseases, immunologic incompatibility, and the weakening of graft mechanical properties caused by sterilization procedures such as gamma irradiation [36].

Because allografts consist of foreign tissue, biological incorporation and remodelling generally occur more slowly than in autografts. Nevertheless, the healing process follows similar phases to autograft ligamentization, during which the graft acts as a scaffold for cellular infiltration, revascularization, and collagen remodelling. Some allografts may also include bone blocks, which can improve graft fixation and facilitate bone-to-bone healing.

Numerous studies comparing autografts and allografts have reported higher failure rates in allograft reconstructions, particularly in younger and highly active patients. Some reports suggest failure rates may be approximately three times higher than those observed with autografts [36]. Consequently, allografts are generally recommended for older patients, revision surgeries, or individuals with lower physical activity demands, most commonly those older than 30 years of age.

Artificial ACL

Due to the limitations associated with graft harvesting and donor-site morbidity, artificial ligaments have emerged as an alternative option for ACL reconstruction. Synthetic grafts

eliminate the need for tendon harvesting and avoid complications related to allograft sterilization and tissue availability. Additionally, their use may reduce operative time and allow earlier rehabilitation.

Early generations of artificial ACLs were associated with high failure rates and poor long-term outcomes. However, significant technological advancements have led to the development of newer synthetic ligaments, particularly the Ligament Advanced Reinforcement System (LARS), which is composed of Polyethylene Terephthalate (PET) fibres [49, 50, 51, 52]. The LARS ligament consists of intra-articular and extra-articular components. The intra-articular portion is designed to mimic the anatomical arrangement of the native ACL, containing longitudinal fibres that replicate the rotational characteristics of ACL bundles. In contrast, the extra-articular segments contain transverse fibres that improve mechanical fixation, which remains one of the principal challenges in synthetic ligament surgery.

Although primary fixation using screws or cortical buttons is essential for stability, osseointegration also contributes to long-term fixation success. One major concern associated with artificial ligaments is the generation of wear particles and debris, which may lead to graft deterioration and mechanical failure, particularly because synthetic materials lack intrinsic healing potential. Foreign body reactions may also occur, potentially leading to aseptic synovitis characterized by joint swelling, pain, and restricted range of motion. To improve biological integration, current research focuses on bioactive coatings and porous scaffold structures that stimulate bone ingrowth around the extra-articular portions of the graft. Similarly, the intra-articular fibres are intentionally less densely packed to permit infiltration of synovial cells and connective tissue into the synthetic structure [50, 51].

Current evidence suggests that LARS demonstrates superior short- and mid-term outcomes compared with earlier synthetic ACL designs, particularly in studies with follow-up periods up to 5 years. However, evidence regarding long-term durability and complication rates remains limited, and further research is necessary to establish their long-term effectiveness and safety [50, 51, 52].

VIII. Discussion

This review focuses on the mechanisms of healing and treatment strategies for ACL rupture. Regardless of the treatment method, the primary objective remains restoration of knee stability and function. However, there is still considerable debate regarding the extent to which restoration of ACL integrity influences long-term patient outcomes, including return to daily activities, sports participation, and development of post-traumatic osteoarthritis.

Several studies have demonstrated that, irrespective of the treatment method used, patients frequently continue to experience knee pain, functional limitations, reduced recreational activity, and impaired quality of life more than 5 years after ACL injury [32]. It has even been suggested that ACL rupture may “age” the knee joint by approximately 30 years [53]. Although restoration of mechanical stability appears insufficient to completely prevent osteoarthritis, some evidence indicates that early surgical intervention combined with appropriate rehabilitation may delay its development and later progression.

Numerous studies have compared the effectiveness of different surgical techniques, often reporting promising clinical outcomes. Nevertheless, many investigations are limited by relatively small sample sizes, short follow-up periods, and heterogeneity in patient populations and rehabilitation protocols. Additionally, randomized studies including untreated control groups are uncommon because withholding treatment may be considered unethical. Assessment of healing and recovery is further complicated by patient-specific variables such as age, activity level, associated injuries, and biological healing potential [32, 33, 35].

Another challenge in evaluating treatment effectiveness is the lack of a universally accepted definition of successful recovery. In some studies, success is defined as restoration of knee stability or absence of graft re-rupture over a defined follow-up period, commonly 5 years. Other studies use return to sport (RTS) as the primary outcome measure. However, RTS itself remains difficult to standardize, as it may refer either to participation in any physical activity or return to the same preinjury level of athletic performance. Additional outcome measures include patient-reported quality of life, functional scores, and the incidence of osteoarthritis.

Each treatment method possesses specific advantages and disadvantages. Non-operative treatment has gained increasing attention in recent years due to a better understanding of the ACL healing process and growing interest in tissue-preserving strategies. This trend is also

reflected in the development of modern ACL repair techniques such as BEAR, DIS, and IBLA, which aim to promote biological healing while preserving native tissue.

For many years, ACL reconstruction was considered the gold standard of treatment, and consequently its benefits and complications are relatively well documented. In comparison, allograft-based procedures and synthetic ligaments have historically received less attention, although increasing numbers of studies are now evaluating their outcomes. Despite promising early results for newer techniques, long-term evidence is still limited. Importantly, no currently available treatment method is entirely failure-proof, and graft or ligament re-rupture may occur even many years after treatment.

Although rehabilitation was only briefly discussed in this review, it remains a fundamental component of ACL treatment. Surgery alone does not restore full knee function. Successful recovery requires a comprehensive rehabilitation program aimed at restoring muscle strength, neuromuscular control, proprioception, range of motion, and functional stability. Close cooperation between the patient, physiotherapist, and surgical team is therefore essential for optimal outcomes.

IX. Conclusions

Current research demonstrates that ligaments, particularly the ACL, are dynamic biological structures with a complex healing capacity influenced by the intra-articular environment. Over the years, multiple treatment strategies have been developed, including reconstruction techniques, primary repair methods, allograft procedures, synthetic ligaments, and non-operative approaches that are based on ACL healing potential or simply mimicking its function.

The choice of treatment depends on numerous factors, including patient age, activity level, type and location of injury, expectations regarding return to sport, and surgeon experience. Although substantial progress has been made in understanding ACL healing and improving surgical techniques, important limitations remain within the current literature. Therefore, further high-quality long-term studies are necessary to better determine the optimal treatment strategies and long-term outcomes following ACL injury.

Disclosure

Author's contribution

Conceptualization: Ewa Tomicka, Justyna Kuś,

Methodology: Natalia Zięba, Anna Brodowska

Software: Anna Knapik, Maciej Ciesielski,

Check: Olgierd Czapiński, Natalia Zięba, Mateusz Pysiewicz,

Formal analysis: Olgierd Czapiński, Patrycja Białowąs,

Investigation: Mateusz Pysiewicz, Natalia Zięba, Justyna Kuś,

Resources: Ewa Tomicka, Anna Knapik, Maciej Ciesielski

Data curation: Justyna Kuś, Olgierd Czapiński,

Writing-rough preparation: Ewa Tomicka, Anna Brodowska

Writing –review and editing: Patrycja Białowąs, Mateusz Pysiewicz,

Visualization: Maciej Ciesielski, Justyna Kuś,

Supervision: Patrycja Białowąs, Anna Knapik,

Project administration: Ewa Tomicka

All authors have read and agreed with the published version of the manuscript.

Financing statement

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable

Data Availability Statement

Not applicable.

Conflict of interest

The authors deny any conflict of interest.

Declaration of the use of generative AI and AI-assisted technologies in the writing process

In preparing this work, the author(s) used Chat GPT for the purpose of verifying bibliographic style, creating visual aspect of the table inserted as well as checking the grammatic and spelling mistakes in the text. After using this tool, the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

Bibliography

- [1] Wright RW, Magnussen RA, Dunn WR, Spindler KP. Ipsilateral graft and contralateral ACL rupture at five years or more following ACL reconstruction: a systematic review. *J Bone Joint Surg Am.* 2011;93(12):1159-1165. doi:10.2106/JBJS.J.00898
- [2] Giuliani JR, Kilcoyne KG, Rue JP. Anterior cruciate ligament anatomy: a review of the anteromedial and posterolateral bundles. *J Knee Surg.* 2009;22(2):148-154. doi:10.1055/s-0030-1247742
- [3] Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J. Anatomy of the anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(3):204-213. doi:10.1007/s00167-005-0679-9

- [4] Morales-Avalos R, Torres-González EM, Padilla-Medina JR, Monllau JC. ACL anatomy: is there still something to learn? *Rev Esp Cir Ortop Traumatol*. 2024;68(4):422-427. doi:10.1016/j.recot.2023.02.005
- [5] Noyes FR. The function of the human anterior cruciate ligament and analysis of single- and double-bundle graft reconstructions. *Sports Health*. 2009;1(1):66-75. doi:10.1177/1941738108326980
- [6] Stocchi R, de Pasquale V, Gubellini P, et al. The human anterior cruciate ligament: histological and ultrastructural observations. *J Anat*. 1992;180(pt 3):515-519.
- [7] Hassebrock JD, Gulbrandsen MT, Asprey WL, Makovicka JL, Chhabra A. Knee ligament anatomy and biomechanics. *Sports Med Arthrosc Rev*. 2020;28(3):80-86. doi:10.1097/JSA.0000000000000279
- [8] Kacprzak B, Stańczak M, Surmacz J, Hagner-Derengowska M. Biophysics of ACL injuries. *Orthop Rev (Pavia)*. 2024;16:126041. doi:10.52965/001c.126041
- [9] Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. *Br J Sports Med*. 2007;41(suppl 1):i47-i51. doi:10.1136/bjism.2007.037192
- [10] Belozo FL, Belozo RSMN, Lopes CR, Yamada AK, Silva VRR. Anterior cruciate ligament: a brief narrative review of main risk factors for injury and re-injury. *J Bodyw Mov Ther*. 2024;38:92-99.
- [11] Alrowaili MG. The impact of age and gender on anterior cruciate ligament injuries and associated knee lesions: a retrospective study. *Cureus*. 2024;16(8):e68200. doi:10.7759/cureus.68200
- [12] Xue Y, Yang S, Sun W, et al. Approaching expert-level accuracy for differentiating ACL tear types on MRI with deep learning. *Sci Rep*. 2024;14:938. doi:10.1038/s41598-024-51666-8
- [13] Smith HC, Vacek P, Johnson RJ, et al. Risk factors for anterior cruciate ligament injury: a review of the literature-part 2: hormonal, genetic, cognitive function, previous injury, and extrinsic risk factors. *Sports Health*. 2012;4(2):155-161. doi:10.1177/1941738111428282
- [14] Arhos EK, Di Stasi S, Hartigan EH, Snyder-Mackler L. Males and females have different muscle activity patterns during gait after ACL injury and reconstruction. *J Electromyogr Kinesiol*. 2022;66:102694. doi:10.1016/j.jelekin.2022.102694
- [15] Parker EA, Duchman KR, Meyer AM, Wolf BR, Westermann RW. Menstrual cycle hormone relaxin and ACL injuries in female athletes: a systematic review. *Iowa Orthop J*. 2024;44(1):113-123.

- [16] Best MJ, Zikria BA, Wilckens JH. Anterior cruciate ligament injuries in the older athlete. *Sports Health*. 2021;13(3):285-289. doi:10.1177/1941738120953426
- [17] Stańczak M, Swinnen B, Kacprzak B, Pacek A, Surmacz J. Neurophysiology of ACL injury. *Orthop Rev (Pavia)*. 2025;17:129173. doi:10.52965/001c.129173
- [18] Xue Y, Yang S, Sun W, et al. Approaching expert-level accuracy for differentiating ACL tear types on MRI with deep learning. *Sci Rep*. 2024;14:938. doi:10.1038/s41598-024-51666-8
- [19] Fayard JM, Sonnery-Cottet B, Vrgoc G, et al. Incidence and risk factors for a partial anterior cruciate ligament tear progressing to a complete tear after nonoperative treatment in patients younger than 30 years. *Orthop J Sports Med*. 2019;7(7):2325967119856624. doi:10.1177/2325967119856624
- [20] van der List JP, Mintz DN, DiFelice GS. The location of anterior cruciate ligament tears: a prevalence study using magnetic resonance imaging. *Orthop J Sports Med*. 2017;5(6):2325967117709966. doi:10.1177/2325967117709966
- [21] Nguyen LT, Truong SV, Nguyen UTP. Value of clinical tests in diagnosing anterior cruciate ligament tears: what is new? *Rev Bras Ortop (Sao Paulo)*. 2025;60(5):s00451813005. doi:10.1055/s-0045-1813005
- [22] Vavken P, Murray MM. The potential for primary repair of the ACL. *Sports Med Arthrosc Rev*. 2011;19(1):44-49. doi:10.1097/JSA.0b013e3182095e5d
- [23] Brzoza J, Werenkiewicz W, Boral A, et al. Current trends in ACL reconstructions: a perspective review of recent literature. *J Educ Health Sport*. 2025;82:60477. doi:10.12775/JEHS.2025.82.60477
- [24] Previ L, Monaco E, Carrozzo A, et al. Spontaneous healing of a ruptured anterior cruciate ligament: a case series and literature review. *J Exp Orthop*. 2023;10(1):11. doi:10.1186/s40634-022-00566-9
- [25] Stamenov N, Yordanova P, Dimitrov D, Telbiyska M, Stefanov M. The epiligament: structure, postnatal development and role in ligament healing. *Cureus*. 2019;11(6):e4836. doi:10.7759/cureus.4836
- [26] Morishita Y, Kanemura N, Kokubun T, Murata K, Takayanagi K. Microscopic observation of a rat spontaneous anterior cruciate ligament healing.
- [27] Blanke F, Trinnes K, Oehler N, et al. Spontaneous healing of acute ACL ruptures: rate, prognostic factors and short-term outcome. *Arch Orthop Trauma Surg*. 2023;143:4291-4298. doi:10.1007/s00402-022-04701-0

- [28] Filbay SR, Roemer FW, Lohmander LS, et al. Evidence of ACL healing on MRI following ACL rupture treated with rehabilitation alone may be associated with better patient-reported outcomes: a secondary analysis from the KANON trial. *Br J Sports Med.* 2023;57(2):91-98. doi:10.1136/bjsports-2022-105473
- [29] Filbay SR, Dowsett M, Chaker Jomaa M, et al. Healing of acute anterior cruciate ligament rupture on MRI and outcomes following non-surgical management with the Cross Bracing Protocol. *Br J Sports Med.* 2023;57(23):1490-1497. doi:10.1136/bjsports-2023-106931
- [30] Komnos GA, Hantes MH, Kalifis G, et al. Anterior cruciate ligament tear: individualized indications for non-operative management. *J Clin Med.* 2024;13:6233. doi:10.3390/jcm13206233
- [31] Cheung EC, DiLallo M, Feeley BT, Lansdown DA. Osteoarthritis and ACL reconstruction-myths and risks. *Curr Rev Musculoskelet Med.* 2020;13(1):115-122. doi:10.1007/s12178-019-09596-w
- [32] Filbay SR, Grindem H. Evidence-based recommendations for the management of anterior cruciate ligament (ACL) rupture. *Best Pract Res Clin Rheumatol.* 2019;33(1):33-47. doi:10.1016/j.berh.2019.01.018
- [33] Zheng H, Zeng Y, Daoerji N, et al. ACL repair vs reconstruction: a meta-analysis of outcomes across different tear characteristics. *BMC Surg.* 2025;25(1):339. doi:10.1186/s12893-025-03101-6
- [34] Runer A, Keeling L, Wagala N, et al. Current trends in graft choice for anterior cruciate ligament reconstruction-part I: anatomy, biomechanics, graft incorporation and fixation. *J Exp Orthop.* 2023;10(1):37. doi:10.1186/s40634-023-00600-4
- [35] Frank RM, Higgins J, Bernardoni E, et al. Anterior cruciate ligament reconstruction basics: bone-patellar tendon-bone autograft harvest. *Arthrosc Tech.* 2017;6(4):e1189-e1194. doi:10.1016/j.eats.2017.04.006
- [36] Iosifidis MI, Tsarouhas A. Allografts in anterior cruciate ligament reconstruction. In: *Sports Injuries.* 2010:421-430. doi:10.1007/978-3-642-15630-4_58
- [37] Vinagre G, Kennedy NI, Chahla J, et al. Hamstring graft preparation techniques for anterior cruciate ligament reconstruction. *Arthrosc Tech.* 2017;6(6):e2079-e2084. doi:10.1016/j.eats.2017.08.031
- [38] Thomson J, Webb M. What are the graft options for anterior cruciate ligament (ACL) reconstruction? *Orthop Rev (Pavia).* 2025;17:143767. doi:10.52965/001c.143767

- [39] Cerulli G, Placella G, Sebastiani E, Tei MM, Speziali A, Manfreda F. ACL reconstruction: choosing the graft. *Joints*. 2013;1(1):18-24.
- [40] Cristiani R, Mikkelsen C, Wange P, et al. Autograft type affects muscle strength and hop performance after ACL reconstruction. A randomised controlled trial comparing patellar tendon and hamstring tendon autografts with standard or accelerated rehabilitation. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(9):3025-3036. doi:10.1007/s00167-020-06334-5
- [41] 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;16(9):e68701. doi:10.7759/cureus.68701
- [42] Lutz PM, Achtnich A, Schütte V, et al. Anterior cruciate ligament autograft maturation on sequential postoperative MRI is not correlated with clinical outcome and anterior knee stability. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(10):3258-3267. doi:10.1007/s00167-021-06777-4
- [43] Janssen RP, Scheffler SU. Intra-articular remodelling of hamstring tendon grafts after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2014;22(9):2102-2108. doi:10.1007/s00167-013-2634-5
- [44] Gopinath V, Touhey DC, Barksdale EM 3rd, Knapik DM. Return to sport after revision anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. Published online January 23, 2026. doi:10.1177/03635465251405493
- [45] Robinson D Jr, Williamson T, Carson T, et al. Primary anterior cruciate ligament repair: current concepts.
- [46] Henle P, Röder C, Perler G, Heitkemper S, Egli S. Dynamic intraligamentary stabilization (DIS) for treatment of acute anterior cruciate ligament ruptures: case series experience of the first three years. *BMC Musculoskelet Disord*. 2015;16:27. doi:10.1186/s12891-015-0484-7
- [47] Shah AK, Neijna AG, Retzky JS, Gomoll AH, Strickland SM. Indications, techniques, and outcomes of bridge-enhanced ACL restoration (BEAR). *Curr Rev Musculoskelet Med*. 2025;18(4):140-148. doi:10.1007/s12178-025-09950-1
- [48] Wilson WT, Hopper GP, Banger MS, Blyth MJG, Riches PE, MacKay GM. Anterior cruciate ligament repair with internal brace augmentation: a systematic review. *Knee*. 2022;35:192-200. doi:10.1016/j.knee.2022.03.009
- [49] Di Benedetto P, Giardini P, Beltrame A, et al. Histological analysis of ACL reconstruction failures due to synthetic-ACL (LARS) ruptures. *Acta Biomed*. 2020;91(4-S):136-145. doi:10.23750/abm.v91i4-S.9702

- [50] Moretti L, Garofalo R, Cassano GD, et al. Anterior cruciate ligament reconstruction with LARS synthetic ligament: outcomes and failures. *J Clin Med.* 2024;14(1):32. doi:10.3390/jcm14010032
- [51] Friel NA, Chu CR. The role of ACL injury in the development of posttraumatic knee osteoarthritis. *Clin Sports Med.* 2013;32(1):1-12. doi:10.1016/j.csm.2012.08.017
- [52] Cheng R, Dimitriou D, Yao G, et al. Outperformance of combined artificial anterolateral ligament and ACL reconstruction compared with isolated artificial ACL reconstruction in knees with anterolateral structure and ACL deficiency: a biomechanical analysis. *Orthop J Sports Med.* 2025;13(2):23259671241309270. doi:10.1177/23259671241309270
- [53] van der List JP, Meixner C, Kaeding CC, Magnussen RA, Flanigan DC. Early anterior cruciate ligament reconstruction is associated with decreased risk of osteoarthritis compared with delayed reconstruction: a systematic review and meta-analysis. *Am J Sports Med.* 2026;54(2):447-456. doi:10.1177/03635465251371330