QUALITY IN SPORT
eISSN 2450-3118 · Open Access · Peer-reviewed
Vol. 55 (2026) · Article 70921 · Published 16.05.2026
apcz.umk.pl/QS · Nicolaus Copernicus University in Toruń

Cite as: Smagoń J, Rafalska I, Kaim M, et al. Autologous Chondrocyte Implantation in Physically Active Patients — A Narrative Review. Quality in Sport. 2026;55:70921. https://doi.org/10.12775/QS.2026.55.70921

ARTICLE TIMELINE
Received: 15.04.2026 **Revised:** 16.05.2026
Accepted: 16.05.2026 **Published:** 16.05.2026

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.

NARRATIVE REVIEW

Autologous Chondrocyte Implantation in Physically Active Patients — A Narrative Review

a narrative review

HIGHLIGHTS

- Focal full-thickness cartilage defects of the knee are a major problem in physically active patients, in whom limited intrinsic repair capacity and high functional demands accelerate symptom development and the risk of early osteoarthritis.
- Autologous chondrocyte implantation (ACI) generates repair tissue closer to native hyaline cartilage than marrow stimulation, producing clinically meaningful improvements in pain and knee function in appropriately selected patients.
- Compared with microfracture, ACI offers more durable mid- and long-term clinical outcomes, particularly in larger lesions (>2–4 cm²) and in younger patients with high functional demands.

▸ Modern matrix-induced ACI (MACI) and scaffold-based tissue engineering have simplified the surgical technique, improved cell distribution, and reduced complications such as graft hypertrophy.
▸ Successful outcomes depend on careful patient selection, correction of malalignment, ligamentous and meniscal stability, and a structured staged rehabilitation programme allowing return to sport at 9–18 months.

AUTHORS & AFFILIATIONS

Jakub Smagoń [JS]
ORCID: https://orcid.org/0009-0008-0109-7349
E-mail: jakubsmagon@gmail.com
Upper Silesian Medical Centre of Prof. Leszek Giec, Medical University of Silesia, Katowice, Poland

Izabela Rafalska [IR]
ORCID: https://orcid.org/0009-0003-1687-8037
E-mail: iza.rafalska@op.pl
Upper Silesian Medical Centre of Prof. Leszek Giec, Medical University of Silesia, Katowice, Poland

Martyna Kaim [MK]
ORCID: https://orcid.org/0009-0001-6818-6732
E-mail: martyna.kaim@onet.eu
District Hospital in Limanowa, Limanowa, Poland

Melania Majewska [MM]
ORCID: https://orcid.org/0009-0009-5334-6965
E-mail: melania.majewska23@gmail.com
County Medical Center in Grójec, Grójec, Poland

Natalia Piasecka [NP]
ORCID: https://orcid.org/0009-0001-2361-8060
E-mail: natalia.piasecka1810@gmail.com
University Clinical Center of the Medical University of Warsaw, Warsaw, Poland

Wiktoria Siewiera [WS]
ORCID: https://orcid.org/0009-0009-1875-0209
E-mail: wsiewiera6@gmail.com
American Heart of Poland, Ustroń, Poland

Joanna Bober [JB]
ORCID: https://orcid.org/0009-0007-0118-885X
E-mail: joannabober09@gmail.com
Provincial Specialist Hospital in Wrocław, Wrocław, Poland

Natalia Kornacka [NK]
ORCID: https://orcid.org/0009-0003-3657-2027
E-mail: leknataliakornacka@gmail.com
Beskid Oncology Center Municipal Hospital of John Paul II, Bielsko-Biała, Poland

Krzysztof Bednarski [KB]
ORCID: https://orcid.org/0009-0000-9801-2832
E-mail: drkrzysztofbednarski@gmail.com
Beskid Oncology Center Municipal Hospital of John Paul II, Bielsko-Biała, Poland

Magdalena Bochenek [MB]
ORCID: https://orcid.org/0009-0006-3997-2810
E-mail: magdabochenek03@gmail.com
Provincial Specialist Hospital in Wrocław, Wrocław, Poland

CORRESPONDING AUTHOR Jakub Smagoń — jakubsmagon@gmail.com

ABSTRACT

BACKGROUND: Focal articular cartilage defects of the knee represent a significant clinical problem, particularly in physically active patients and individuals with high functional demands, leading to pain, functional limitation, and increased risk of early osteoarthritis. Due to the limited intrinsic healing capacity of hyaline cartilage, multiple reparative strategies have been developed, among which autologous chondrocyte implantation (ACI) remains one of the most important cell-based procedures in modern clinical practice.

AIM: The aim of this study was to summarize current evidence regarding the biological background, surgical techniques, clinical efficacy, patient selection, and rehabilitation of ACI, with particular emphasis on its role in physically active patients and restoration of functional activity.

MATERIALS AND METHODS: This study was designed as a structured narrative review synthesizing current evidence on cartilage biology, pathophysiology of focal defects, classification systems, operative treatment options, ACI and MACI techniques, biomaterials, clinical outcomes, complications, patient selection, and rehabilitation, with consideration of increased functional demands.

RESULTS: Available evidence indicates that ACI enables restoration of repair tissue with properties more similar to hyaline cartilage compared with marrow stimulation techniques and leads to clinically meaningful improvement in pain and knee function. This is particularly relevant in physically active patients and individuals with high functional demands, in whom durable outcomes are critical. Compared with microfracture, ACI appears to provide more durable clinical outcomes; however, treatment effectiveness depends strongly on appropriate patient selection, correction of biomechanical abnormalities, and structured postoperative rehabilitation.

CONCLUSIONS: ACI represents an advanced and clinically valuable treatment option for physically active patients with focal knee cartilage defects. Despite favorable outcomes, the procedure remains technically demanding and requires further optimization. Future directions include personalized regenerative strategies aimed at improving functional recovery and long-term maintenance of physical activity.

KEYWORDS autologous chondrocyte implantation; ACI; MACI; articular cartilage; cartilage defects; knee joint; cartilage regeneration; tissue engineering; physically active patients; physical activity; functional recovery

1. INTRODUCTION

Articular cartilage is a highly specialized connective tissue covering the osseous surfaces of synovial joints, enabling nearly frictionless movement and facilitating the transmission and uniform distribution of mechanical loads across the joint surface [1]. These biomechanical properties are essential for maintaining normal knee function, particularly as the knee joint is exposed to substantial mechanical stress during daily activities. Preservation of cartilage integrity is therefore crucial for protecting subchondral bone and maintaining physiological joint biomechanics [1].

Focal cartilage defects represent a clinically significant problem, particularly relevant in physically active patients, in whom cartilage injuries are often associated with repetitive joint loading and increased functional demands. Arthroscopic studies have demonstrated a high prevalence of chondral lesions in patients undergoing knee procedures, highlighting their frequent occurrence in orthopedic practice [2]. If left untreated, these defects may progress and contribute to degenerative joint changes, chronic pain, and functional impairment. A major therapeutic challenge arises from the limited regenerative capacity of hyaline cartilage, which is avascular and characterized by low cellularity, resulting in minimal intrinsic healing potential following injury [3,4].

In response to these biological limitations, various cartilage repair techniques have been developed, among which autologous chondrocyte implantation (ACI) has emerged as a well-established treatment option for larger cartilage defects of the knee. ACI is particularly considered in cases where less invasive methods fail to provide satisfactory outcomes [5]. Clinical studies indicate significant improvements in knee function and patient-reported outcomes at 12 and 24 months following ACI in appropriately selected patients [5].

The increasing incidence of focal cartilage defects, together with the rapid development of regenerative and cell-based therapies, underscores the need for a comprehensive evaluation of the current role of ACI in contemporary

orthopedic practice. This review aims to provide an integrative analysis of ACI, with particular emphasis on its biological basis, surgical techniques, clinical effectiveness, patient selection, rehabilitation strategies, and future perspectives within evolving treatment algorithms. Therefore, effective cartilage repair strategies are essential not only for symptom relief but also for restoring functional capacity and enabling return to an active lifestyle.

Research Objective.

The objective of this study is to critically evaluate current evidence regarding autologous chondrocyte implantation in the management of focal cartilage defects of the knee, with particular emphasis on biological rationale, operative techniques, clinical effectiveness, limitations, and future directions.

Research Problems.

What biological and biomechanical factors determine the success of cartilage repair?

How does ACI compare with marrow stimulation and osteochondral grafting techniques?

Which patients are optimal candidates for ACI?

What is the clinical value of modern modifications such as MACI and scaffold-based tissue engineering approaches?

Research Hypotheses.

ACI enables the generation of repair tissue more closely resembling hyaline cartilage compared with marrow stimulation techniques.

ACI provides more durable clinical outcomes than microfracture in larger defects.

Optimal treatment results depend on appropriate patient selection, correction of coexisting pathology, and structured postoperative rehabilitation.

Modern scaffold-based and combined regenerative strategies may further improve clinical outcomes.

2. MATERIALS AND METHODS

This study was designed as a structured narrative review focusing on focal cartilage defects of the knee and the role of autologous chondrocyte implantation in their management. The review synthesizes current scientific evidence related to cartilage structure and function, the pathophysiology of cartilage damage, classification systems, surgical repair strategies, autologous chondrocyte implantation (ACI) and matrix-induced autologous chondrocyte implantation (MACI) techniques, biomaterials, tissue engineering approaches, patient selection, complications, postoperative rehabilitation, and future regenerative strategies.

A targeted literature-based approach was applied using key search concepts, including "autologous chondrocyte implantation," "ACI," "MACI," "articular cartilage," "cartilage defects," "knee joint," "cartilage regeneration," and "tissue engineering." The narrative framework was designed to provide a clinically oriented synthesis of available evidence rather than a quantitative meta-analysis. The literature selection prioritized clinically relevant publications, including randomized controlled trials where available, review articles, and foundational studies addressing cartilage biology and surgical treatment principles. Particular emphasis was placed on evidence relevant to orthopedic decision-making, long-term functional outcomes, and the biological quality of repair tissue. The manuscript also incorporates practical clinical considerations related to indications, contraindications, correction of biomechanical abnormalities, and postoperative rehabilitation strategies.

Artificial intelligence tools were used exclusively for linguistic refinement of the manuscript. All scientific interpretation, selection of content, and conclusions were performed by the authors.

3. RESULTS

3.1. Articular cartilage: structure, function, and pathophysiology

Articular cartilage is a specialized connective tissue characterized by a highly organized extracellular matrix [1,6]. Its principal functions are to provide a low-friction articulating surface and to distribute mechanical forces across the knee joint [1]. The extracellular matrix of hyaline cartilage is composed predominantly of type II collagen and proteoglycans, particularly aggrecan [7]. These components determine elasticity, compressive resistance, hydration, and overall biomechanical integrity [1,7]. Owing to its glycosaminoglycan content and high water-binding capacity, aggrecan plays a key role in shock absorption during axial loading [7]. Chondrocytes are the only resident cells within articular cartilage and are responsible for synthesis, remodeling, and maintenance of extracellular matrix homeostasis [6,7].

Under physiological conditions, chondrocytes demonstrate low proliferative and metabolic activity, although they remain responsive to mechanical, inflammatory, and biochemical stimuli [6]. Because articular cartilage is avascular, alymphatic, and aneural, its spontaneous healing potential is markedly limited [3]. Focal cartilage injury has only limited self-repair capacity because the absence of vascularity prevents effective influx of reparative cells and healing mediators into the lesion site [3]. When the subchondral plate is not penetrated, the biological repair response remains minimal and defects tend to progress under continued mechanical loading [8]. Mechanical trauma leads to disruption of the type II collagen network, depletion of aggrecan, increased tissue hydration, matrix disorganization, and secondary chondrocyte dysfunction [7]. Local inflammatory activation, oxidative stress, and increased expression of matrix metalloproteinases and aggrecanases further accelerate tissue degeneration [9]. Prolonged instability of the intra-articular microenvironment may induce apoptosis or phenotypic dedifferentiation of chondrocytes, resulting in progressive loss of biomechanical competence [9]. From a structural perspective, native hyaline cartilage is characterized by highly ordered architecture, predominance of type II collagen, and optimal mechanical performance [3]. Fibrocartilage, in contrast, contains a greater proportion of type I collagen and demonstrates lower resistance to long-term compressive and shear loading [8]. This distinction is clinically relevant because most marrow stimulation procedures generate fibrocartilaginous repair tissue, which is biologically and functionally inferior to native hyaline cartilage [8].

3.2. Classification systems and risk factors

In clinical practice and research, cartilage lesion severity is commonly graded using the International Cartilage Repair Society (ICRS) classification [10]. This system ranges from grade 0, representing normal cartilage, to grade 4, indicating full-thickness cartilage loss with exposure of the subchondral bone [10].

Another classical grading system is the Outerbridge classification, originally developed for patellofemoral lesions and later applied more broadly to knee cartilage pathology [11]. In this system, grade I denotes cartilage softening, grade II includes fragmentation and fissuring, grade III corresponds to deeper fissures, and grade IV reflects exposed subchondral bone. Both systems remain clinically useful for selecting surgical treatment and comparing study populations.

The most important risk factors for focal knee cartilage defects include sports-related trauma, ligamentous injuries, meniscal tears, and direct compressive-shear trauma to the articular surface [12]. Ligamentous insufficiency leads to abnormal joint kinematics, altered force transmission, and repetitive microtrauma

affecting cartilage integrity. Malalignment of the lower extremity, particularly varus or valgus deformity, represents a major risk factor for both cartilage injury and failure of reparative procedures [12]. Meniscal deficiency, ligamentous instability, and malalignment should therefore be corrected when indicated.

Increased body mass index is associated with a higher prevalence of cartilage defects, reduced cartilage volume, and impaired biomechanics [12]. High physical activity, particularly in contact and pivoting sports, also increases injury risk, especially in the presence of biomechanical abnormalities. Repetitive joint loading and high levels of physical activity contribute to increased mechanical stress on articular cartilage, predisposing physically active individuals to focal defects.

3.3. Role of surgical treatment in focal cartilage defects

Surgical treatment plays a central role in patients with persistent symptoms despite conservative management [13]. The primary goals are pain reduction, restoration of joint function, and slowing of degenerative progression.

Marrow stimulation techniques, such as microfracture, induce formation of repair tissue through bone marrow activation; however, the resulting tissue is predominantly fibrocartilage and therefore biomechanically inferior [8]. Although effective in the short term, durability is limited, particularly in active patients.

Osteochondral autograft transfer (OATS) enables restoration of the articular surface using mature hyaline cartilage but is limited by donor-site morbidity and graft availability [8]. Osteochondral allografts allow treatment of larger defects but are restricted by availability and logistical factors.

These limitations have driven the development of advanced regenerative approaches, among which autologous chondrocyte implantation occupies a central role [10].

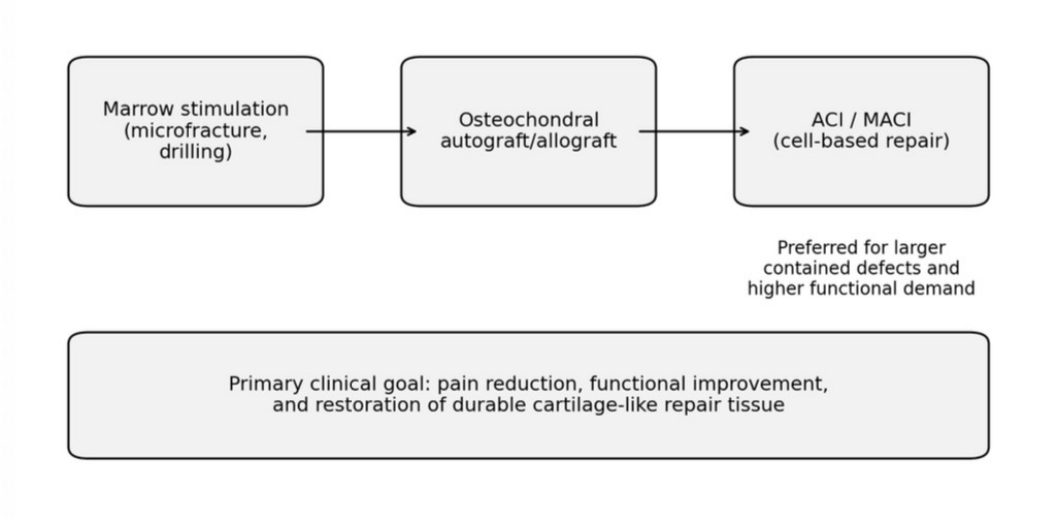

Figure 1. Position of ACI among selected surgical strategies for focal cartilage defects. *Source: authors' own elaboration based on the reviewed literature.*

3.4. Autologous chondrocyte implantation: biological basis and evolution of the technique

Autologous chondrocyte implantation is an advanced biological method designed to restore cartilage with properties closer to hyaline tissue [10]. The technique involves harvesting autologous chondrocytes, their in vitro expansion, and subsequent implantation into the cartilage defect.

First-generation ACI involved implantation of a suspension of cultured chondrocytes beneath a periosteal patch. Although early clinical results were promising, this technique was associated with complications such as graft hypertrophy and uneven cell distribution [10].

Second-generation ACI introduced collagen membranes, which improved control of the implantation environment and reduced complication rates. Third-generation techniques, including matrix-induced autologous chondrocyte implantation (MACI), utilize three-dimensional scaffolds that provide a more physiological environment for chondrocyte proliferation and differentiation [14].

ACI is typically performed as a two-stage procedure. The first stage involves arthroscopic harvesting of healthy cartilage, followed by cell isolation and expansion. The second stage consists of implantation of cultured chondrocytes into the prepared defect. Successful integration depends on proper defect preparation and stable fixation of the implant.

The mechanism of action is based on proliferation of implanted chondrocytes and synthesis of extracellular matrix components, including type II collagen and proteoglycans, which contribute to restoration of cartilage structure and function [14].

3.5. Modern ACI techniques: MACI, biomaterials, and tissue engineering

The development of ACI has been closely linked to advances in biomaterials and tissue engineering, both of which aim to improve the biological quality of repair tissue and optimize conditions for cell survival and differentiation [14,15].

Matrix-induced autologous chondrocyte implantation (MACI) represents the current standard scaffold-based approach. In this technique, chondrocytes are cultured on a biodegradable scaffold, most commonly collagen-based, and subsequently implanted into the cartilage defect. This allows for more uniform cell distribution and improved spatial organization, promoting regeneration of tissue resembling native hyaline cartilage [15].

Compared with earlier ACI techniques, MACI is associated with simplified surgical procedures, shorter operative time, and reduced complication rates. Clinical studies have demonstrated significant improvements in pain and joint function, as well as favorable long-term outcomes.

Biomaterials play a crucial role in regulating cell behavior. Collagen scaffolds, synthetic biodegradable polymers, and hydrogels are widely used to support cell adhesion, proliferation, and extracellular matrix synthesis [15].

Tissue engineering strategies integrate cells, scaffolds, and biological signals such as growth factors. Among the most important are TGF-β, IGF-1, and BMPs, which stimulate chondrogenesis and matrix production [16].

Emerging approaches include the use of mesenchymal stem cells and three-dimensional bioprinting techniques, which enable the creation of constructs tailored to defect geometry. Despite promising results, widespread clinical implementation remains limited by cost and lack of standardization.

3.6. Clinical outcomes and efficacy of ACI

Autologous chondrocyte implantation has been extensively evaluated in clinical studies and is considered an effective treatment option for focal cartilage defects of the knee, particularly in young and physically active patients [2,17]. In this population, restoration of joint function and the ability to return to previous levels of physical activity represent key outcome measures.

Most studies demonstrate significant improvement in pain, joint function, and quality of life following ACI. This method appears particularly beneficial in patients with high functional demands, where long-term durability of repair tissue is critical.

Comparative studies between ACI and microfracture indicate that both techniques may provide short-term clinical improvement; however, the advantage of ACI becomes more pronounced over longer follow-up periods [17]. In studies exceeding two to five years, ACI demonstrates superior functional outcomes and greater durability of benefit. These differences are primarily attributed to repair tissue quality, as ACI produces hyaline-like cartilage, whereas microfracture results in fibrocartilage with limited mechanical resilience [18].

Meta-analytic data suggest that ACI is particularly advantageous in larger lesions, typically exceeding 2–4 cm², and in patients with high functional demands [17,18]. Younger patients appear to benefit most from ACI, especially in the context of return to sport.

Comparisons between ACI and osteochondral autograft transfer indicate that both techniques may yield favorable outcomes, although their indications differ. Osteochondral autograft transfer is more suitable for smaller lesions, whereas ACI is preferable in larger defects [8].

Long-term follow-up studies confirm sustained pain reduction and functional improvement after ACI [2]. Imaging studies further demonstrate progressive maturation of repair tissue toward a hyaline-like structure.

3.7. Indications and patient qualification for ACI

Proper patient selection is one of the most critical determinants of successful ACI. Outcomes depend not only on lesion characteristics but also on overall joint condition and biomechanical environment [12,19].

ACI is primarily indicated for medium-sized and large focal cartilage defects, typically exceeding 2–4 cm². Smaller lesions may be more appropriately treated with marrow stimulation or osteochondral grafting techniques. The best results are generally achieved in full-thickness defects with preserved surrounding cartilage.

Patient age is an important factor, with optimal outcomes observed in younger and middle-aged individuals who retain higher regenerative potential. High functional demand, including sports activity, is also considered a favorable indication. This is especially relevant in physically active individuals, for whom sustained joint performance is essential for maintaining quality of life.

An essential requirement is the absence of advanced osteoarthritis, as ACI is intended for focal rather than diffuse cartilage degeneration [19]. Joint biomechanics must be carefully evaluated, including ligamentous stability, meniscal integrity, and lower-limb alignment. Instability, meniscal deficiency, and malalignment should be corrected when present to optimize treatment outcomes.

Elevated body mass index represents an adverse prognostic factor due to increased mechanical loading and pro-inflammatory effects [12]. For these reasons, patient qualification for ACI should be individualized and multidisciplinary.

3.8. Complications and limitations of ACI

Despite favorable clinical outcomes, ACI is associated with specific complications and limitations that must be considered during treatment planning [20,21]. One of the most commonly reported complications of first-generation ACI is graft hypertrophy, particularly when a periosteal patch is used. This may lead to pain, mechanical symptoms, and the need for revision procedures [10]. The introduction of second- and third-generation techniques, including MACI, has significantly reduced this complication. Incomplete graft integration represents another important issue and may result in implant instability and deterioration of clinical

outcomes. Factors contributing to poor integration include suboptimal defect preparation, persistent biomechanical overload, and impaired biological healing capacity.

Because ACI is a two-stage procedure, it involves cumulative surgical risk, including infection, hematoma, and donor-site morbidity. A major biological limitation is chondrocyte dedifferentiation during in vitro expansion, which reduces the ability to produce stable hyaline-like tissue [16].

Additional limitations include high procedural complexity, requirement for specialized laboratory infrastructure, and substantial cost. Lack of standardization across techniques, rehabilitation protocols, and outcome assessment further complicates comparison between studies.

3.9. Rehabilitation after ACI

Rehabilitation is a critical component of successful ACI treatment, as graft maturation and integration depend on controlled mechanical loading and a favorable intra-articular environment [13,22].

Postoperative rehabilitation is typically divided into three phases: protection, progressive loading, and return to function. During the early phase, emphasis is placed on graft protection through restricted weight-bearing and controlled range of motion. Continuous passive motion is frequently used to maintain joint mobility and support cartilage nutrition.

In the intermediate phase, gradual loading is combined with muscle strengthening and neuromuscular training. The later phase focuses on restoration of full function, including strength, proprioception, and dynamic stability. Appropriate mechanical loading is essential for cartilage maturation, as it stimulates extracellular matrix synthesis. Both excessive loading and insufficient stimulation may impair regeneration. Return to sport typically occurs between 9 and 18 months postoperatively and depends on lesion characteristics and adherence to rehabilitation protocols. Resumption of physical activity represents a major goal of rehabilitation and requires not only biological healing but also restoration of strength, neuromuscular control, and joint stability.

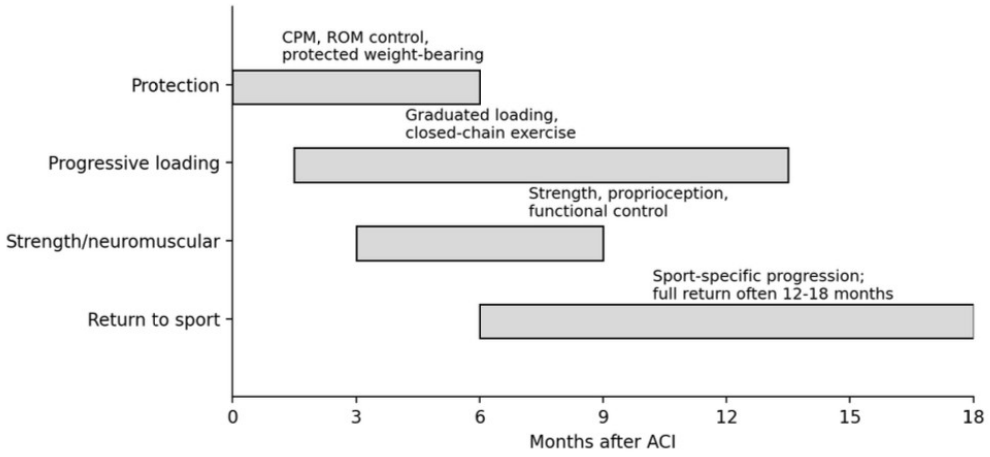

Figure 2. Simplified rehabilitation timeline after autologous chondrocyte implantation. *Source: authors' own elaboration based on the reviewed literature.*

3.10. Future directions and combined strategies

Current approaches to cartilage repair are increasingly focused on integrated regenerative strategies combining cell-based therapy, biomaterials, and biological modulation of the joint environment [16,23].

One important direction involves combining ACI with biological adjuvants such as platelet-rich plasma and growth factors, which may enhance chondrocyte activity and improve graft integration [15]. Another promising strategy is the integration of ACI with mesenchymal stem cells, which provide both chondrogenic potential and immunomodulatory effects [23]. Advances in biomaterials have led to the development of increasingly sophisticated scaffolds that better mimic native cartilage structure. Three-dimensional bioprinting enables precise fabrication of implants tailored to defect geometry and allows controlled spatial distribution of cells and materials.

Gene and molecular therapies represent an emerging area of research, focusing on modulation of key regulatory pathways involved in cartilage regeneration. Although still largely experimental, these approaches may significantly enhance regenerative potential in the future.

Finally, increasing emphasis is placed on personalized treatment strategies, taking into account patient-specific factors such as age, activity level, biomechanics, and inflammatory status. Future therapeutic algorithms will likely integrate surgical techniques, cell-based therapies, biomaterials, and individualized rehabilitation into a comprehensive treatment model.

4. DISCUSSION

The findings of this review indicate that autologous chondrocyte implantation remains one of the most biologically advanced approaches to the treatment of focal cartilage defects of the knee. The available evidence demonstrates that its principal advantage over marrow stimulation techniques lies in its ability to promote repair tissue with properties more closely resembling hyaline cartilage [8,10]. From a clinical perspective, the management of focal cartilage defects is particularly important in physically active patients due to their increased functional demands and joint loading.

This distinction is clinically relevant because the biological quality of the repair tissue is strongly associated with durability of symptom relief and long-term preservation of joint function. In physically active patients, treatment success is closely associated with restoration of function and the ability to maintain an active lifestyle.

Although microfracture may provide satisfactory short-term improvement in smaller lesions, its limitations become more evident in larger defects and in young, high-demand patients, in whom fibrocartilaginous repair tissue often fails to maintain function over time [2,17].

The current evidence supports ACI as particularly valuable in patients with high functional demands, where durability of repair tissue is essential [2,17]. However, the procedure should not be interpreted as an isolated technical intervention. Successful outcomes depend on a broader orthopedic strategy that includes correction of malalignment, restoration of ligamentous stability, preservation or reconstruction of meniscal function, and implementation of a structured rehabilitation program [13,19]. Failure to address these associated factors may explain a substantial proportion of unsatisfactory outcomes reported in clinical practice.

The development of MACI and other scaffold-based techniques has significantly improved the safety and practicality of cell-based cartilage repair by reducing periosteal complications and providing a more favorable microenvironment for chondrocytes [14,15]. At the same time, important biological challenges remain, including dedifferentiation during in vitro expansion and variability in cell quality between patients [16]. These limitations justify continued investigation into optimized culture conditions, scaffold design, growth-factor delivery, and combined regenerative strategies involving stem cells or molecular modulation [23].

From a clinical perspective, ACI should be regarded as a high-value but resource-intensive treatment. The procedure remains technically demanding, requires a two-stage therapeutic pathway, and is associated with

considerable cost [13,19]. For this reason, its role appears strongest in patients requiring a durable restorative option and in whom lesion characteristics and clinical profile justify a biologically advanced intervention. Future progress in regenerative orthopedics will likely depend on improved standardization of treatment protocols and increasing personalization of therapeutic pathways.

Taken together, the available evidence supports the view that ACI occupies an important place in contemporary cartilage restoration algorithms, particularly in younger patients with focal full-thickness defects and high functional demands. These considerations are particularly relevant in physically active populations, where restoration of joint function directly translates into maintenance of daily and recreational activity levels. Its long-term value appears to depend not only on the surgical technique itself but also on careful integration of biological, biomechanical, and rehabilitation-related factors within a comprehensive treatment strategy.

4.1. Limitations of the study

This study has several limitations related to its narrative design, including the lack of quantitative synthesis of pooled outcomes and the potential for selection bias in the reviewed literature. In addition, heterogeneity of available studies, differences in surgical techniques, variability in rehabilitation protocols, and incomplete standardization of outcome assessment limit direct comparability of published results. Nevertheless, the structured approach applied in this review allows for a clinically oriented interpretation of the evidence across biological, surgical, and rehabilitation domains.

5. CONCLUSIONS

Autologous chondrocyte implantation represents an advanced therapeutic option for the treatment of focal articular cartilage defects of the knee, enabling restoration of repair tissue with properties closer to hyaline cartilage and providing clinically meaningful improvement in pain and joint function.

Compared with marrow stimulation techniques, ACI offers greater durability of clinical benefit, particularly in patients with larger lesions and higher functional demands.

Treatment success is strongly influenced by appropriate patient selection and optimization of biomechanical and structural joint conditions.

A structured rehabilitation program remains essential for graft integration, tissue maturation, and restoration of functional activity.

Future developments are likely to focus on combined regenerative strategies and personalized treatment approaches aimed at improving long-term outcomes and maintaining physical activity levels in physically active patients.

DISCLOSURE

Author Contributions

Conceptualization: Jakub Smagoń, Izabela Rafalska. Methodology: Jakub Smagoń, Martyna Kaim, Izabela Rafalska. Writing — original draft preparation: Izabela Rafalska, Jakub Smagoń, Martyna Kaim, Joanna Bober, Magdalena Bochenek, Wiktoria Siewiera, Melania Majewska, Natalia Piasecka, Natalia Kornacka, Krzysztof Bednarski. Writing — review and editing: all authors. Supervision: Izabela Rafalska, Martyna Kaim. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new datasets were generated or analyzed in this review.

Acknowledgements

The authors thank all contributors involved in the preparation of this manuscript.

Conflicts of Interest

The authors report that there is no conflict of interest.

REFERENCES

1. Fox AJS, Bedi A, Rodeo SA. The basic science of articular cartilage: structure, composition, and function. Sports Health. 2009;1(6):461–468. doi:10.1177/1941738109350438

2. Randsborg PH, et al. Focal cartilage defects in the knee: a randomized controlled trial comparing autologous chondrocyte implantation with arthroscopic debridement. BMC Musculoskelet Disord. 2016;17:117. doi:10.1186/s12891-016-0969-z

3. Hunziker EB. Articular cartilage repair: basic science and clinical progress. Osteoarthritis Cartilage. 2000;8(3):161–166. doi:10.1053/joca.1999.0334

4. Liu Y, Shah K, Luo J. Strategies for articular cartilage repair and regeneration. Front Bioeng Biotechnol. 2021;9:770655. doi:10.3389/fbioe.2021.770655

5. Henderson I, Tuy B, Oakes B, Hettwer W. Autologous chondrocyte implantation for treatment of focal chondral defects of the knee. Knee. 2005;12(3):175–184. doi:10.1016/j.knee.2004.07.005

6. Poole AR. Articular cartilage chondrons: form, function and failure. J Anat. 2001;199(1–2):1–13. doi:10.1046/j.1469-7580.2001.19910001.x

7. Karuppal R. Current concepts in articular cartilage repair and regeneration. J Orthop. 2017;14(2):A1–A3. doi:10.1016/j.jor.2017.05.001

8. Minas T, Nehrer S. Current concepts in the treatment of articular cartilage defects. Orthopedics. 2010;33(9):659. doi:10.3928/01477447-20100722-42

9. Martel-Pelletier J, Barr AJ, Cicuttini FM, et al. Osteoarthritis. Nat Rev Dis Primers. 2016;2:16072. doi:10.1038/nrdp.2016.72

10. Brittberg M, Lindahl A, Nilsson A, Ohlsson C, Isaksson O, Peterson L. Treatment of deep cartilage defects in the knee with autologous chondrocyte transplantation. N Engl J Med. 1994;331(14):889–895. doi:10.1056/NEJM199410063311401

11. Outerbridge RE. The etiology of chondromalacia patellae. J Bone Joint Surg Br. 1961;43-B:752–757. doi:10.1302/0301-620X.43B4.752

12. Silverwood V, Blagojevic-Bucknall M, Jinks C, et al. Current evidence on risk factors for knee osteoarthritis in older adults: a systematic review and meta-analysis. Osteoarthritis Cartilage. 2015;23(4):507–515. doi:10.1016/j.joca.2014.11.019

13. Jevsevar DS, et al. The American Academy of Orthopaedic Surgeons evidence-based guideline on osteoarthritis of the knee. J Bone Joint Surg Am. 2013;95(20):1885–1886. doi:10.2106/JBJS.M.00688

14. Kon E, et al. Biological treatments for cartilage regeneration. J Knee Surg. 2013;26(1):1–8. doi:10.1055/s-0033-1334174

15. Filardo G, Kon E, Buda R, et al. Platelet-rich plasma intra-articular injections for cartilage degeneration and osteoarthritis: single- versus double-spinning approach. Knee Surg Sports Traumatol Arthrosc. 2011;19(4):528–535. doi:10.1007/s00167-010-1238-6

16. Caplan AI, Correa D. The MSC: an injury drugstore. Cell Stem Cell. 2011;9(1):11–15. doi:10.1016/j.stem.2011.06.008

17. Dai WL, Zhou AG, Zhang H, Zhang J. Efficacy of platelet-rich plasma in the treatment of knee osteoarthritis: a meta-analysis of randomized controlled trials. Arthroscopy. 2017;33(3):659–670.e1. doi:10.1016/j.arthro.2016.09.024

18. Bannuru RR, Schmid CH, Kent DM, et al. Comparative effectiveness of pharmacologic interventions for knee osteoarthritis: a systematic review and network meta-analysis. Ann Intern Med. 2015;162(1):46–54. doi:10.7326/M14-1231

19. Kolasinski SL, et al. 2019 American College of Rheumatology/Arthritis Foundation guideline for the management of osteoarthritis of the hand, hip, and knee. Arthritis Care Res. 2020;72(2):149–162. doi:10.1002/acr.24131

20. Wernecke C, Braun HJ, Dragoo JL. The effect of intra-articular corticosteroids on articular cartilage: a systematic review. Orthop J Sports Med. 2015;3(5):2325967115581163. doi:10.1177/2325967115581163

21. McAlindon TE, LaValley MP, Harvey WF, et al. Effect of intra-articular triamcinolone vs saline on knee cartilage volume and pain. JAMA. 2017;317(19):1967–1975. doi:10.1001/jama.2017.5283

22. Hochberg MC, et al. American College of Rheumatology recommendations for the use of nonpharmacologic and pharmacologic therapies in osteoarthritis of the hand, hip, and knee. Arthritis Care Res. 2012;64(4):465–474. doi:10.1002/acr.21596

23. Freitag J, et al. Mesenchymal stem cell therapy in the treatment of osteoarthritis: reparative pathways, safety and efficacy. Regen Med. 2016;11(4):389–401. doi:10.2217/rme-2016-0008