Surgical Restoration/Repair of Articular Cartilage Injuries in Athletes

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Abstract: Articular cartilage injuries of the knee are an increasingly common source of pain and dysfunction, particularly in the athletic population. In the athlete, untreated articular cartilage defects can represent a career threatening injury and create a significant obstacle in returning to full athletic participation. The markedly limited healing potential of articular cartilage often leads to continued deterioration and progressive functional limitations. Numerous studies have shown that full thickness articular cartilage lesions are frequently encountered at the time of arthroscopy, particularly associated with athletic injury. A variety of surgical treatment options exist, including debridement, microfracture, osteochondral autograft, osteochondral allograft, and autologous chondrocyte implantation. Each technique has advantages and limitations for restoring articular cartilage function, and emerging technology continues to improve the results of treatment. Our article provides an evidence-based review on the etiology and prevalence of articular cartilage injuries in athletes, along with the principles and techniques available for restoring articular cartilage function following injury.

Keywords: articular cartilage injury; microfracture; osteochondral autograft transplantation; osteochondral allograft; autologous chondrocyte implantation

Introduction
Injury to the articular cartilage of the knee is a common occurrence in sports participants. Orthopedic surgeons have been treating chondral injuries of the knee for > 250 years. Although treatment modalities have changed considerably during this time period, articular cartilage injuries still present a difficult challenge for patients who sustain them and the physicians who treat them. Articular cartilage has limited potential to heal, and cartilage lesions left untreated often lead to progressive degenerative changes and arthritis. We review the current treatment options available for patients with articular cartilage lesions of the knee, with an emphasis on the biologic basis for repair.

Prevalence
Articular cartilage defects of the knee are a frequently encountered injury, particularly in the athletic population. A recent review of > 30,000 arthroscopic procedures of the knee by Curl et al revealed that > 60% of patients had evidence of Grade III or IV chondral lesions. When the patient population in this study was restricted to age ≤ 40, a 5% incidence of Grade IV chondral defects was noted. Similarly, a more recent review of 1000 consecutive knee arthroscopies by Hjelle et al revealed nearly identical results; > 60% of patients had evidence of articular cartilage pathology, 19% had a
focal chondral defect, and 5.3% of patients aged < 40 years had evidence of Grade III or Grade IV chondral lesions. Another series of 1010 knee arthroscopies performed at the authors’ institution for patients with meniscal pathology, found a similarly high prevalence of chondral changes and articular cartilage damage (Figure 1 A and 1B). Overall, 48% of patients showed changes in the medial compartment, 45% in the patellofemoral compartment, and 25% to the lateral compartment. Age and body mass index (BMI) were found to be statistically significant factors associated with increased chondral injury. A recent review of 704 MRI scans of National Football League Combine participants showed a 17.4% prevalence of full thickness articular cartilage lesions. With increasing participation in both high-level and recreational sports, the frequency of sports-related articular cartilage injury is only expected to continue to increase. Although articular cartilage injury is known to cause pain and limit mobility in the general population, it is particularly problematic for athletes involved in high-impact, pivoting sports. The increased joint stresses and shear forces experienced by this high-demand population can exacerbate the deleterious effects of articular cartilage injuries and prohibit a return to pre-injury athletic participation.

**Etiology**

Injuries to the articular cartilage can be described as acute, chronic, or acute on chronic. It has been estimated that 5% to 10% of full thickness cartilage lesions result from direct trauma. Articular cartilage injuries often occur in conjunction with meniscal or ligamentous injuries, and acute patellar dislocations. Some studies have shown that ≤ 50% of athletes, particularly females, undergoing anterior cruciate ligament (ACL) reconstruction have concomitant articular cartilage defects of the femoral condyles. Chronic articular cartilage injuries can result from repetitive trauma and joint loading that induce irreversible changes in cartilage biochemical composition.

Articular cartilage is primarily composed of type II collagen surrounded by an extracellular matrix of approximately 65% to 85% water. Chondrocytes and other extracellular proteins, such as proteoglycans, are embedded within this matrix. The chondrocytes found in articular cartilage reside in a relatively avascular environment; they depend heavily on diffusion from synovial fluid and surrounding tissues for nutrition and support. Mature chondrocytes also lack intrinsic potential for replication and repair exhibited by other undifferentiated precursor cells. Such precursor cells are notably absent from the articular cartilage microenvironment. This absence of undifferentiated repair cells combined with an avascular environment results in a profound reduction in healing potential for articular cartilage. Untreated, articular cartilage injury leads to increased hydration of this microenvironment, fissuring of the articular surface, and disruption of the overall collagen architecture.

The collagen architecture of articular cartilage can be divided into several distinct zones with collagen orientation designed to optimize different functions. The first zone is known as the superficial layer and primarily resists shear stress because collagen fibers are oriented parallel to the joint surface. The next layer represents a transitional layer between the superficial layer and the deep layer. Here, collagen fibers are obliquely oriented and resist primarily compressive forces. The deep zone has collagen fibers oriented perpendicular to the subchondral plate and also resists compressive forces. The underlying subchondral plate...
separates articular cartilage from marrow and progenitor cells located within the metaphysis of adjacent bone. This division contributes to the limited healing potential seen in articular cartilage injuries. Any attempts to repair articular cartilage require restoration of both the complex collagen architecture and functional zones so that both functional and durability of the repair cartilage are provided.

**Clinical Evaluation**

Although the symptoms of articular cartilage injuries are frequently nonspecific, patients will often present with pain localized to the affected compartment. Catching, locking, and swelling are commonly reported. A detailed physical exam should be performed on the patient with attention to other possible pathology, including ligamentous or meniscal injury, patellofemoral maltracking, and limb malalignment. Patients with articular cartilage injuries will often exhibit joint line tenderness and recurrent effusions are frequently found. Patients with lesions of the trochlea or patella will often have a positive patellar grind test and pain with deep squatting. In any patient who presents with recurrent effusions with a nonspecific exam, there should be suspicion of an articular cartilage injury.

Radiographic evaluation should include standing anteroposterior and lateral views, axial patella/Merchant view, and a 45-degree flexion posteranterior (PA) weight-bearing view. Weight-bearing views, including the 45-degree flexion PA view, are critical to evaluate for subtle flexion joint-space narrowing and early arthritic development. If clinical suspicion warrants, full, long-leg mechanical axis radiographs can be ordered to evaluate limb alignment. The mechanical axis should pass through the center of the knee. Any varus or valgus deviation will have a negative effect on cartilage repair technique and should be corrected at the time of surgery to optimize results. Following plain radiographs, magnetic resonance imaging (MRI) is frequently used to confirm the presence of articular cartilage defects as well as any other associated ligamentous or meniscal injury. Evolving MRI techniques, such as high Tesla magnets and cartilage-specific sequences, provide excellent detail and resolution between articular cartilage, synovial fluid, and subchondral bone. Evaluation for bone loss from traumatic lesions or osteochondritis dissecans, as well as significant bone marrow edema or avascularity, can affect ultimate treatment recommendations. The sensitivity and specificity of MRI for detecting articular cartilage injuries continue to improve and MRI is a valuable tool in preoperative planning. In addition, staging arthroscopy plays a significant role in identifying the multitude of factors that may affect cartilage restoration techniques, including the amount of bone loss, size, location, containment and shouldering of affected areas, the presence of multiple lesions requiring treatment, and the possibility of meniscal deficiency.

**Treatment Options**

The goals of treatment for articular cartilage injuries in the athlete include reducing pain and symptoms and return to pre-injury level of competition. To re-iterate, the drastically limited healing potential of articular cartilage makes nonoperative treatment less effective in many cases. The natural history of untreated, symptomatic articular cartilage lesions frequently results in continued pain and patient dissatisfaction. A National Institutes of Health (NIH) consensus conference on osteoarthritis (OA) showed a 4.4 to 5.3 relative risk for the development of knee arthritis in athletes with articular cartilage injuries who participate in high-demand, pivoting sports. A Swedish study followed 28 athletes with severe chondral damage of the weight-bearing femoral condyles and found a significant decline in athletic participation. More than 57% of the study patients exhibited signs of knee arthritis on radiographic imaging at 14 years following the initial injury. Operative treatment of articular cartilage injuries is traditionally divided into 2 categories, reparative and restorative. The 2 most often used reparative techniques are microfracture and subchondral drilling. These surgical techniques rely on marrow stimulation and recruitment of mesenchymal precursor cells to form a fibrocartilage repair at the injury site. Breaching the subchondral plate may allow progenitor cells to surround the defect and cause fibrocartilage patch formation. Fibrocartilage repair is distinctly different from articular hyaline cartilage. It is comprised of mostly type I collagen as compared to the predominance of type II collagen in normal articular hyaline cartilage. Additionally, fibrocartilage lacks the architectural framework typical of articular cartilage. Restorative treatment techniques, however, do not rely on fibrocartilage repair but instead aim to restore articular hyaline cartilage at the lesion site. The 3 main categories of restorative techniques include osteochondral autograft transplantation (OATS), osteochondral allograft transplantation, and autologous chondrocyte implantation (ACI). All 3 categories rely on restoration of hyaline cartilage at the site of articular injury for optimal results.
Debridement And Marrow Stimulation

First described by Magnusson in 1946, debridement, microfracture, and subchondral drilling represent some of the earliest forms of treatment for articular cartilage injury.\(^\text{18}\) Initial treatment attempts relied largely on simple debridement and removal of loose bodies. McEldowney and Weiker reviewed a case series of 11 patients who underwent simple debridement from 1982 to 1991. All 11 patients had significant pain reduction and were able to return to preoperative activities for an average of 6 more years before either requiring additional surgery or reporting limitations in activity level.\(^\text{19}\) Another study compared the results of arthroscopic abrasion and debridement compared with debridement alone in treating patients with Grade IV chondromalacia.\(^\text{20}\) Using Hospital for Special Surgery (HSS) knee scores, 66% of patients in the debridement-alone group had good to excellent results at 5-year follow-up compared with only 51% good to excellent results in patients in the abrasion group. Other studies, however, have not reported such positive, long-term results. Debridement alone only provides temporary relief because the underlying cartilage defect is never fully addressed. While debridement represented the most common initial treatment of articular cartilage injury, efforts over time focused on bridging the subchondral plate to stimulate fibrocartilage repair. In 1956, Pridie described drilling of sclerotic subchondral bone to stimulate smooth fibrocartilage ingrowth.\(^\text{21}\) Although initially done through an arthrotomy, the advent of arthroscopy allowed for the conversion of an open surgery to a much less invasive arthroscopic approach to treatment. Further development of drilling and abrasive techniques aimed at removing subchondral bone continued; however, thermal necrosis, a major side effect of motorized drilling, led to unsatisfactory results. The technique of microfracture was developed to address the problems associated with thermal necrosis from drilling. Although the subchondral plate is still breached with microfracture, the major difference in surgical technique is the specialized tools or awls used to penetrate the bony cortex.\(^\text{22}\) Microfracture utilizes specialized awls that are tapped through the subchondral cortex, approximately 3 mm to 4 mm apart, to a depth of 3 mm to 4 mm, until marrow droplets are exposed from bone; no drilling is performed (Figure 2). Although thorough debridement and removal of the calcified layer of cartilage is necessary to provide an adequate scaffold for fibrocartilage growth, no drilling is performed and the risk of thermal necrosis is eliminated.

Microfracture is the most often used technique for marrow stimulation and offers several distinct advantages. The relative simplicity, low cost, and minimal morbidity associated with microfracture surgery makes it an appealing first-line treatment for small (< 2 sq cm) lesions. However, the durability of the fibrocartilage patch tissue used to cover such lesions postoperatively has come into question in terms of durability (at > 24 months), especially patients who are athletes. Fibrocartilage compared with normal hyaline cartilage has inferior stiffness and poorer wear characteristics. Steadman et al evaluated > 70 knees following microfracture and found 80% had clinical improvement at 7 years’ follow-up.\(^\text{23}\) Mithoefer, however, evaluated microfracture outcomes in athletes participating in high-impact sports and found only a 66% rate of good to excellent results at 2-year follow-up.\(^\text{24}\) Other studies have shown deterioration of knee function in 47% to 80% of athletes 2 years post-microfracture, despite good initial clinical improvement.\(^\text{25,26}\) Critics of marrow stimulation cite the suboptimal nature of fibrocartilage repair tissue compared with healthy articular cartilage as a main reason for the development of restoration techniques in the treatment of articular cartilage lesions. We currently use microfracture as a first-line treatment for patients with

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**Figure 2.** A. Arthroscopic photo of full thickness 15 × 12-mm articular cartilage lesion of trochlea. B. Arthroscopic photo: Following microfracture, the lesion is debrided to stable vertical borders, and holes are placed 3 mm to 4 mm apart. C. Bleeding from the lesion following microfracture.
smaller lesions (< 2 sq cm) on the femoral condyles with limited bone loss, particularly in patients aged < 40 years.

**Restoration Techniques**

The 3 current most commonly used restoration techniques for patients with articular cartilage lesions are osteochondral autograft transplantation (OATS), osteochondral allograft, and autologous chondrocyte implantation (ACI). Although there are subtle differences among the techniques, all 3 attempt to produce a hyaline cartilage repair at the site of injury.

Osteochondral autograft transplantation was described as early as 1908 by Judet et al. Although the procedure has been much enhanced since then, the basic principle has remained the same. With OATS, small, cylindrical osteochondral plugs are harvested from minimal weight-bearing areas of hyaline-covered articular surfaces, usually the intercondylar notch or the lateral trochlea. The borders of the cartilage defect are debrided to a stable rim, appropriately sized recipient holes are made in the base of the defect, and the donor plugs are press fit into place. The press fit is a critical aspect of the procedure in order to secure a stable fixation, while reproducing an anatomic radius of curvature of the articular surface. Although technically demanding, achieving congruity and graft height alignment are essential to minimizing contact pressures and enhancing peripheral integration of graft tissue. Because healthy articular cartilage tissue must be sacrificed from other areas of the knee, OATS are generally limited to lesions of ≤ 4 cm².

Hangody et al. popularized an arthroscopic version of OATS with a nearly 95% good-to-excellent result at 32 months. In a later study, > 830 patients undergoing OATS procedures for articular cartilage lesions showed positive clinical results based on a variety of outcome rating scales. Good to excellent results were found post-procedure in 92% of patients with femoral lesions, 87% with tibial lesions, and 79% of patients with trochlear or patellar lesions during a 10-year period. Another prospective study conducted specifically in athletes over a 24- to 36-month period showed good to excellent results in 95% of patients. Despite significant weight-bearing limitations in the postoperative period, 61% to 93% of athletes in the study were reported to return to play at 6 to 9 months after undergoing. Another study (2005) compared microfracture with mosaicplasty in the treatment of articular cartilage lesions, averaging 2.5 cm² in the knees of young, active athletes. At a follow-up of 37 months, 93% of athletes treated with mosaicplasty were able to return to pre-injury levels of play compared with 52% of those who underwent microfracture. At 10-year follow-up, the mosaicplasty group had a 14% failure or re-operation rate compared with a 38% failure rate for those who had undergone microfracture. While patient outcomes after OATS appear positive, several limitations, including donor site morbidity and the technical demands of maintaining articular surface congruity exist, so that OATS are best suited in cases where patients have smaller sized (1–4 cm²) lesions. We prefer to use OATS for smaller lesions (< 2 cm sq) where bone loss is present.

Osteochondral allograft transplantation, on the other hand, is not limited by donor site availability and thus can be used to repair much larger cartilage defects. First reported in 1908 by Lexer, osteochondral allograft transplantation follows the same general principles as OATS; a donor osteochondral dowel graft is press fit into a prepared osseous bed, followed, over time, by integration and incorporation of the graft. The donor cartilage in allograft transplantation is typically harvested and implanted as a single piece instead of the multiple plugs used with OATS. Care and detail are taken to correctly match the lesion and donor depth and shape in order to accurately recreate an anatomical curvature of articular surface. Osteochondral allografts can be particularly useful when there are significant bone defects, such as the treatment of osteochondritis dissecans (OCD) (Figure 3 A–C).

Initial results for patients having undergone allograft transplantation appear promising. In a review of 122 patients with isolated femoral cartilage lesions treated with allograft transplantation, nearly 91% were reported to have a successful outcome at 5 years. A similar study of 122 patients with lesions of the femur, tibia, and patella treated with allograft transplantation demonstrated successful outcomes in 85% of patients. Although initial results are encouraging, the duration of allograft transplantation endurance has come into question. One study revealed deterioration of results over time with graft survival at 95% at 5 years, 80% at 10 years, and only 65% at 15 years. The immediate survivorship of osteochondral allografts has also been a subject of debate. Although donor morbidity with allograft transplantation is not an issue, the availability of suitable cadaver specimens can be problematic. Chondrocyte death in fresh, cryopreserved specimens can begin 2 to 3 weeks after procurement, creating logistical challenges and increasing the cost associated with the procedure. Williams et al examined whether chondrocyte death translates into inferior clinical results through a review of 19 fresh allografts with a mean storage time of 30 days (17–42 days). At 25 months post-procedure, 18
of 19 patients had a functional outcome score improvement and normal cartilage thickness.

Studies examining the results of allograft transplantation in athletes specifically have been lacking. One recent study by Krych et al reviewed 43 athletes with large, symptomatic chondral defects treated with osteochondral allograft transplantation. At 2.5-year follow-up, 38 of 40 athletes (88%) were able to return to sports, with 34 athletes (79%) exhibiting a full return to their pre-injury level of competition.

Although osteochondral allograft transplantation provides a reasonable solution to large articular cartilage defects, the high cost, logistical challenges, and theoretical risk of disease transmission in a young, active population warrant further investigation into the use of this technique in athletes. Another disadvantage to treatment using osteochondral allografts is the significant bone defect created to place the graft. This could potentially “burn bridges” for future repair if the graft fails or is not incorporated. We currently use osteochondral allografts for large lesions of the femoral condyles or trochlea, particularly when significant bone loss is present.

Introduced in Sweden in the early 1990s, and first published by Brittberg in 1994, ACI is another method of cartilage restoration. Indicated primarily for full thickness defects ranging from 2 cm² to 10 cm², ACI is a 2-stage process. The first stage includes a diagnostic arthroscopy and cartilage biopsy from a minimal weight-bearing area of the joint. Approximately 200 mg to 300 mg of chondrocytes or 2 “large tic-tac”-sized, full thickness samples (5 × 8 mm) are biopsied and steriley transported to the laboratory for amplification. The samples are cultured and processed in the laboratory for approximately 3 weeks, when the chondrocytes are ready for reimplantation. During the second stage of ACI, a small arthrotomy is made, and the cartilage lesion is prepared and debrided back to a stable rim. A periosteal patch is then sewn over the lesion site and secured with 6–0 absorbable suture. After the patch is sewn into place, a sterile saline syringe is used to check for a watertight seal. Once the seal is ensured, the saline is removed, and the prepared chondrocytes are injected underneath the patch, which is then reinforced with fibrin glue, concluding the procedure (Figure 4 A, B).

Minas et al demonstrated an 87% improvement rate in 169 patients at a minimum of 1-year follow-up. In 2002, Petersen reported on the long-term durability of ACI and showed 82% good to excellent results at 2 years post-procedure, and 83% good to excellent results at 5 to 11 years after the procedure. Several studies have shown positive results of ACI in athletes as well. In 2005, Mitchoefer studied 45 soccer
players with lesions (average lesion, 5.7 cm$^2$). Following ACI, 72% of the athletes showed good to excellent results.\textsuperscript{44} Patient satisfaction scores in the study athletes ranged from 60% to 90%, with the best results found in athletes with isolated lesions of the medial femoral condyle. Nearly 83% of the competitive level soccer players were able to return to play. The results were even more favorable in adolescent athletes, where 90% were able to return to play.\textsuperscript{44} According to a Swedish study (2010), the positive results seen with ACI appear longstanding, with patient satisfaction as high as 92% at 10 to 20 years following the procedure.\textsuperscript{45} An additional study from Sweden by Moradi et al, had a clinical follow-up of patients ranging from 7 to 14 years following ACI.\textsuperscript{46} More that 50% of the patients had MRI evidence of complete defect filling at final follow up and nearly 75% of patients said they would undergo the procedure again.\textsuperscript{46}

The results of ACI for treatment of patellofemoral lesions appear to be very encouraging, with several studies reporting good to excellent results in > 85% of patients.\textsuperscript{47} Although recreating the natural contours of the trochlea poses a technical challenge, ACI offers a promising treatment option for patients with large lesions of the patellofemoral joint. The success of ACI for treating patellofemoral lesions is further enhanced when combined with corrective osteotomies or realignment procedures, such as anteromedial translation of the tibial tubercle. Also known as the Fulkerson technique,\textsuperscript{48} anteromedialization of the tibial tubercle has been shown in several biomechanical cadaver studies to decrease total trochlear contact pressure and decrease lateral contact pressures through a medial shift. Unloading the trochlea and patella appears essential in optimizing the results of ACI; earlier studies demonstrated good outcomes in only 30% of patients who had not undergone a concomitant corrective osteotomy.\textsuperscript{44} A recent meta-analysis by Trinh et al demonstrated significantly greater improvements in multiple clinical outcomes for patients undergoing ACI and a corrective osteotomy compared with using ACI alone.\textsuperscript{49} An additional study by Cole et al demonstrated similar, superior results for patients who underwent a realignment procedure in conjunction with ACI of the patellofemoral joint compared with patients who underwent ACI only (75% vs 45% satisfaction rate, respectively).\textsuperscript{50}

There are disadvantages for treatment with ACI, including high cost and the need for a staged procedure. The most common complication for patients who have undergone ACI is periosteal overgrowth, with a re-operation rate ≤ 26% for arthroscopy and debridement. Recently, the use of a porcine patch (Bio-Gide\textsuperscript{®}) has significantly decreased the rate of periosteal overgrowth following ACI. In addition, there are several newer techniques for cartilage transplantation available in Europe, including matrix-induced ACI (MACI) that have shown promising results in athletes. Also known as “second-generation ACI,” MACI uses temporary, biodegradable scaffolds, such as protein or carbohydrate polymers (polyglycolic acid, hyaluronan, collagen, fibrin, etc), to support the implanted chondrocytes until they begin synthesizing their own matrix components. The theoretical benefits of MACI include reduced graft hypertrophy, less chondrocyte leakage, and a more homogenous chondrocyte
distribution. One study, using a hyaluronic-acid–based scaffold, showed an improvement in knee function in 90% of patients, with particularly promising results seen in athletes and those aged < 30 years.31 Another series of 40 patients who underwent MACI with a polyglactin matrix scaffold exhibited good defect filling on MRI, hyaline-like tissue at 1-year biopsy, and significant improvement in knee outcome scores at 2-year follow-up.52 We currently use ACI as first-line treatment for patients with large articular cartilage lesions of femoral condyles, trochlea, and patella, when minimal bone loss is present, as well as for second-line treatment for smaller lesions.

As ACI technique has developed and progressed, several studies comparing ACI with existing articular cartilage lesion treatment methods have been undertaken. In 2005, Fu et al compared treatment results of ACI with those of debridement and found that patients who underwent ACI exhibited greater pain relief and a higher level of function at a minimum follow-up of 3 years.53 However, a randomized controlled trial by Knutsen et al compared the short-term results of microfracture with ACI in 80 patients at 2-year follow-up and no significant outcome differences were found.54 Critics of the study, however, cite the short-term follow-up as a major drawback of the reported results, especially considering other studies that have demonstrated a deterioration of knee function in 47% to 80% of patients undergoing microfracture after just 24 months.33,55 A more recent study comparing microfracture with ACI results was conducted in 41 professional soccer players; 21 treated with ACI and 20 treated with microfracture.56 Although both groups exhibited similar results at 2-year follow-up, results in the microfracture group seemed to deteriorate over time. At 4 to 7.5 years of follow-up, patient satisfaction and clinical outcome scores in the microfracture group continued to decline while the ACI group exhibited much more durable results. Bentley et al compared ACI with mosaicplasty treatment in 100 patients and found good to excellent results in 88% of the ACI-treated patients compared with 69% of patients treated with mosaicplasty.48 At second-look arthroscopy (at 1-year follow-up), 82% of the ACI-treated patients and 34% of the mosaicplasty-treated patients had evidence of an excellent repair. Horas et al, however, compared results of ACI with results of OATS in 40 patients with isolated femoral condyle lesions ranging from 3.2 to 5.6 cm² and found no difference in outcomes between the 2 groups.57

In athletes’ knees with articular cartilage defects, other concomitant pathologies frequently coexist, including meniscal tears, ligamentous instability, and malalignment. Several recent studies have shown that addressing the other pathologies at the same time as the articular cartilage defects is essential to obtain satisfactory results.58,59 Kish et al showed that treatment of patient ACL or meniscal injuries at the time of mosaicplasty did not affect recovery time or return to play of high-level athletes.31 Mithoefer exhibited similar return-to-play results in athletes undergoing ACI and combined ACL reconstruction, high tibial osteotomy, or meniscal repair.60 Another recent study demonstrated better outcomes for patients who underwent microfracture and concomitant ACL reconstruction than for those who underwent microfracture surgery alone.61 The results of these studies have important implications for athletes eagerly awaiting return to play. Simultaneous treatment of all knee pathology helps avoid staged procedures and prolonged rehabilitation that would further delay many athletes’ resumption of activity.

We present our current algorithm for the treatment of articular cartilage injuries in athletes in Figure 5A and B. Several factors help determine the best treatment option for a patient, including the size of the lesion, amount of underlying bone loss, and the patient’s demand and age. Additionally, there are other patient and lesion factors, including the location or presence of multiple lesions, other concomitant pathology (such as meniscal deficiency), and malalignment, all of which may alter the preferred treatment in any particular patient. Method of treatments need to be individualized, and the algorithm simply serves as a basic guide to treatment.

Rehabilitation

While the selection of a specific surgical treatment technique remains important, perhaps even more essential to ensuring successful patient outcomes is the adoption of and adherence to a dedicated rehabilitation program postoperatively. Protecting the surgical repair and fostering cartilage restoration often necessitates lengthy restrictions in weight bearing and activity, posing a difficult limitation for many of the active athletes undergoing treatment for articular cartilage lesions. Rehabilitation programs should be individualized for each patient and several variables such as; lesion size and location; patient age, previous activity level, and general health; and the specific surgical technique used all need to be taken into account when developing a postoperative treatment plan. In general, most patients benefit from protected weight bearing and early continuous passive motion for a period of 6 weeks. Strict non-weight bearing and immobilization of the knee have been shown to have deleterious effects on cartilage repair.62,63 Gentle passive range of motion promotes diffusion and movement.
of synovial fluid about the knee, providing nutrition at the site of cartilage repair and stimulating matrix and proteoglycan production.64 One study involving microfracture patients in particular demonstrated 85% satisfactory results for those who used continuous passive motion (CPM) for 6 to 8 hours per day for 8 weeks compared to 55% satisfactory results for patients who underwent microfracture alone.65 Several arthroscopic and animal studies have given an inside examination of the repair site at different stages of the healing process.66–68 Based on these studies, repair of the articular cartilage has generally been broken up into four biological phases of healing; proliferation, transitional, remodeling, and maturation. Although the duration of each phase will vary based on the specific surgical technique employed, the general principles of rehabilitation in each phase remain the same.69 Protection of the repair with gentle passive range of motion and partial weight bearing is imperative in the proliferation phase which can last anywhere from 4 to 8 weeks. As the repair tissue gains strength and matrix production continues in the transitional phase, weight bearing is generally advanced to full and active range of motion is instituted. In the cases of OATS and osteochondral allograft, bone plug integration is typically complete by weeks 4–6, at which time weight bearing can be progressed to full as well. During the remodeling phase, the 3-dimensional architecture of the cartilage repair is enhanced and strengthened. At this time, generally 3–6 months after initial surgery, all activities of daily living as well as low impact conditioning such as elliptical and bicycle training can commence. During the maturation phase, the repair tissue begins to achieve its full strength and durability. Higher impact and sport specific training can be gradually incorporated during this time period. However, it can take up to a year or longer for athletes to fully return to sport specific participation. Although a multitude of variables including surgery type and lesion size make the prediction of return to play difficult, in general most athletes in non contact sports such as running or jogging are able to return in 10–12 months while athletes in high-impact, pivoting sports often require 12–18 months to fully recover.69–70 One study by Steadman et al examined return to play for National Football League (NFL) players following microfracture surgery for full thickness chondral lesions of the knee.71 In their study, 19 out of 25 players (76%) returned to play the following season following microfracture surgery, averaging 4.6 seasons or 56 more games in their professional career. Nine players or 36% were still active in the NFL at the time of publication. As previously mentioned, a study by Mithoefer et al. evaluated the return to play for soccer players following ACI repair.45 The results of this study appear mixed; although nearly 83% of high skill level players (defined as high school, collegiate, or professional level) returned to competition, only 16% of recreational soccer players returned to the game. Average time to return to play was also shorter for the high level athletes when compared to recreational players, 14.2 months versus 22.2 months respectively ($P < 0.001$). An additional study by Mithoefer et al examined adolescent athletes in particular and showed a nearly 96% return to high impact sports following ACI.59 They did note that duration of preoperative symptoms correlated strongly with ability to return to preinjury level of competition; nearly all adolescents that had preoperative symptoms $>1$ year. A recent metanalysis by Mandelbaum et al compiled twenty studies with over 1300 patients.72 Return to sport was possible for 73% of all athletes combined, with highest rates found for patients having undergone OATS repair (91%). Similarly, the average time to return to sports participation varied with each repair technique; 8 months for microfracture, 7 months for OATS, and 18 months for ACI. Although return to play is an almost universally held goal among athletes undergoing cartilage repair, the long-term effects of returning to sport for these individuals has yet to
be determined. Further studies examining the durability of the various treatment methods for articular cartilage injury repair are warranted, particularly in athletes that return to competition. The long-term effects of returning to play, including any possible association with the development of secondary OA, need to be evaluated in this population.

Future treatments of articular cartilage injuries are continually being analyzed and developed. The main goal of all developing treatment methods is the improvement of repair tissue quantity and quality. Third-generation ACI techniques are attempting to implant “neocartilage” generated from chondrocytes cultured in special bioreactors that promote extracellular matrix production. Controlled hydrostatic pressures in the bioreactors stimulate the harvested chondrocytes to produce matrix proteins inside a bovine collagen sponge. The neocartilage unit is then implanted, theoretically leading to shorter rehabilitation time, and, thus, a quicker return to play for athletes because the in vivo matrix production phase has been bypassed. Peripheral integration, adequate cartilage fill, and an 86% pain relief rate at 2-year follow-up have been demonstrated in recent phase I trials. Second-generation microfracture techniques employ various thrombogenic and adhesive polymers to enhance 3-D fibrocartilage organization and increase progenitor cell recruitment. Some of the latest developments in articular cartilage treatment include mesenchymal stem cell therapy (MSC). The MSCs found in bone marrow, skin, and adipose tissue are harvested and, under appropriate cell signaling pathways in the laboratory, differentiate into articular cartilage cells suitable for implantation into knee cartilage defects. Hui et al compared MSC transplants with OATS, cultured chondrocytes, and periosteal grafts in animal models of osteochondritis dissecans. The MSC transplants were found to be comparable with cultured chondrocytes and superior to periosteal and OATS in the repair of cartilage defects. Another study using MSCs derived from easily accessible adipose cells consistently filled chondral defects in a rodent mode. Adipose-derived stem cells (ASCs) are currently being examined for use in the repair of cartilage defects. Although still in development, stem cells will likely play a large role in articular cartilage injury treatment in the near future.

Summary

Articular cartilage damage in the athlete represents the possibility of significant injury that could markedly limit athletic participation, even to the point of being career threatening. The limited healing potential of articular cartilage has restricted the effectiveness of nonoperative treatment, particularly for those patients who are athletes. Several surgical treatments for lesions of the articular cartilage exist with the primary goals of reduction of pain, restoration of function, and return to play. The operative techniques for articular cartilage repair can be broadly divided into reparative and restorative methods. Microfracture surgery is reparative and relies on fibrocartilage repair at the lesion site. Restorative techniques attempt to recreate hyaline cartilage at the lesion site and include OATS, osteochondral allograft transplantation, and ACI. Each technique has specific limitations and advantages and the choice of repair technique should be individualized to patient and lesion characteristics. Addressing concomitant knee pathology at the time of articular cartilage lesion repair or restoration is essential in order for the athlete to return to pre-injury levels of play. Improvements in available techniques and novel approaches, using stem cells, gene therapy, biologic scaffolds, and local growth factors, continue to evolve. Long-term studies and additional randomized controlled trials that directly compare the different treatment methods are needed to guide future therapy efforts, especially for the athletic population.

Conflict of Interest Statement

Patrick Kane, MD, Robert Frederick, MD, Christopher Dodson, MD, and John Anderson, MD, and Kevin B. Freedman, MD, disclose no conflicts of interest. Michael G. Ciccotti, MD, discloses that he is a member of the advisory board/committee of Arthrex and a consultant for Stryker. Bradford Tucker, MD, discloses that he is a member of the advisory board/committee of DePuy Orthopaedics, Inc. and Zimmer; an consultant with DePuy Orthopaedics, Inc., Knee Creations, LLC, and Mirtek LLC; a member of the speakers bureau for Johnson and Johnson and Knee Creations, LLC; and a patent holder with Knee Creations, LLC.

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