[CLINICAL COMMENTARY]

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Current Concepts for Rehabilitation and Return to Sport After Knee Articular Cartilage Repair in the Athlete

Acute and chronic injuries of the articular cartilage surfaces of the knee are frequently observed in athletes. A recent systematic review demonstrated an average prevalence of full-thickness focal chondral defects in 36% of athletes.[49] Defects were located predominantly in the patellofemoral compartment (37%) and femoral condyles (35%), and less frequently on the tibial plateau (25%). Magnetic resonance imaging (MRI) evaluation of asymptomatic professional basketball players revealed articular cartilage abnormalities in the knee of up to 89% of the players,[181] and cartilage injury has been reported to exist in 20% of professional American football players.[19] Levy et al[96] demonstrated an increasing incidence of chondral injuries over time in competitive collegiate, professional, and world-class-level soccer players. In addition to the rising incidence of such injuries in high-level competitive athletes, the increase in recreational participation in pivoting sports such as football, basketball, and soccer has been associated with a rising number of sports-related articular cartilage injuries in that population.[6] Injuries of the articular cartilage surface of the knee in the athlete frequently occur in association with other injuries, such as ligament or meniscal tears, traumatic patellar dislocations, and osteochondral injuries.[104] Articular cartilage defects of the femoral condyles have been observed in up to 50% of athletes undergoing anterior cruciate ligament reconstruction, with an increased incidence in female athletes.[143] Articular cartilage defects can also develop in the high-impact athletic population from chronic, pathologic joint-loading patterns that result from joint instability or malalignments.[104] Irrespective of their origin, articular cartilage injuries will frequently limit the ability of the affected athletes to continue participation in their sport and predispose them to progressive joint degeneration.[88]

The limited ability of spontaneous repair following acute or chronic articular cartilage injury is well documented.[77] The lack of vascularization of articular cartilage prevents the physiologic inflammatory response to tissue injury and resultant repair. This failure of recruitment of extrinsic, undifferentiated repair cells combined with the intrinsic inability for replication and repair by mature chondrocytes results in a repair cartilage that is both qualitatively and quantitatively insufficient. Repetitive loading of the injured articular cartilage, as occurs in impact and pivoting sports, results in

SYNOPSIS: Articular cartilage injury is observed with increasing frequency in both elite and amateur athletes and results from the significant acute and chronic joint stress associated with impact sports. Left untreated, articular cartilage defects can lead to chronic joint degeneration and athletic and functional disability. Treatment of articular cartilage defects in the athletic population presents a therapeutic challenge due to the high mechanical demands of athletic activity. Several articular cartilage repair techniques have been shown to successfully restore articular cartilage surfaces and allow athletes to return to high-impact sports. Postoperative rehabilitation is a critical component of the treatment process for athletic articular cartilage injury and should take into consideration the biology of the cartilage repair technique, cartilage defect characteristics, and each athlete's sport-specific demands to optimize functional outcome. Systematic, stepwise rehabilitation with criteria-based progression is recommended for an individualized rehabilitation of each athlete not only to achieve initial return to sport at the preinjury level but also to continue sports participation and reduce risk for reinjury or joint degeneration under the high mechanical demands of athletic activity. *J Orthop Sports Phys Ther 2012;42(3):254-273. doi:10.2519/jospt.2012.3665*

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further cellular degeneration with the accumulation of degradative enzymes and cytokines, disruption of collagen ultrastructure, increased hydration, and fissuring of the articular surface.[100] In a long-term study[115] that examined the knees of 28 young athletes with isolated, severe chondral damage, 75% of these athletes initially returned to sport; but a significant decline of athletic activity and resultant reduction of sports participation were observed 14 years after the initial injury. However, most patients continued to engage in individual fitness activities, 22 of whom were satisfied with their knee function. Radiographic evidence of osteoarthritis was present in 57% of these athletes, with older athletes having a higher incidence of arthritic changes than younger athletes. These results are consistent with an up to 12-fold increased risk of knee osteoarthritis in high-demand, pivoting athletes.[36,88]

Intact articular cartilage possesses optimal load-bearing characteristics and adjusts to the level of activity and the loading demands of the joint. Increasing weight-bearing activity in athletes and adolescents has been shown to increase the volume and thickness of articular cartilage.[79,80] In the healthy athlete, a positive linear dose-response relationship exists for repetitive-loading activities and articular cartilage function.[84,100] However, recent studies in a canine model indicate that this dose-response curve reaches a threshold and that activity beyond this threshold can result in maladaptation and injury of articular cartilage.[84] High-impact joint loading beyond the capabilities of the cartilage has been shown to decrease cartilage proteoglycan content, increase levels of degradative enzymes, and cause chondrocyte apoptosis.[84,100] If the integrity of the functional weight-bearing unit (articular cartilage, menisci, ligaments, muscle) is lost, either through acute injury or chronic microtrauma in the high-impact athlete, a chondropenic response is initiated that can include loss of articular cartilage volume and stiffness, elevation of contact pressures, and development or progression of articular cartilage defects. Concomitant pathologic factors such as ligamentous instability, malalignment, and meniscal injury or deficiency can further promote degenerative progression.

Despite recent advances in surgical techniques to address articular cartilage injuries, recovery to previous levels of activity is often delayed. Because of the vulnerable nature of articular cartilage repairs, especially in the initial healing stages, postsurgical rehabilitation of the athlete has been identified as critically important, with the potential to influence both patient outcome and quality of repair tissue.[118] However, limited evidence-based research exists on rehabilitation after chondral repairs, especially in the athletic population.[32,56,62,147] Therefore, the purpose of this current-concepts paper is to discuss postoperative rehabilitation of the athlete following an articular cartilage repair procedure in the knee. The overall goal of postoperative rehabilitation is to maximize patient recovery and outcomes, while facilitating cartilage healing and maturation and preventing risk of further chondrocyte death or injury. The development and implementation of criteria-based guidelines are presented to inform clinical decision making and guide rehabilitation progression from acute phases through return to sport.

CARTILAGE SURGICAL TECHNIQUES

Treatment of articular cartilage injuries in the athletic population has traditionally presented a significant therapeutic challenge due to the limited capacity for spontaneous repair. However, development of new surgical techniques has created considerable clinical and scientific enthusiasm for articular cartilage repair. Based on the source of the cartilage repair tissue, these surgical techniques can generally be categorized into restorative and reparative procedures. Restorative procedures restore articular cartilage without neocartilage repair tissue and include osteochondral autograft transfer system (OATS) and allograft transplantation. In contrast, reparative procedures are designed to produce a repair cartilage tissue and include marrow stimulation techniques using mesenchymal stem cells (first- and second-generation microfracture techniques) and all early and advanced chondrocyte-based repair techniques (autologous chondrocyte transplantation [ACI], characterized chondrocyte implantation, and matrix-induced autologous chondrocyte implantation). A recent survey[19] of National Football League team physicians reported that microfracture was the most frequent treatment approach (43%), followed by debridement (31%), nonoperative treatment (13%), OATS (6%), osteochondral allograft (4%), and, last, chondrocyte-based repair (3%). Chondral lesion size was the most important factor in decision making to determine the surgical technique.

Restorative Cartilage Repair Techniques

The use of OATS for repair of focal chondral and osteochondral lesions has been popularized by Hangody et al.[63] This technique provides a hyaline cartilage restoration by harvesting cylindrical osteochondral grafts from areas of limited weight bearing (the intercondylar notch or the medial and lateral trochlea), which are transferred into small to midsize (1-4 cm^2) defects of the weight-bearing joint surface using a press-fit technique. This technique does not involve regeneration of a cartilage repair tissue. While immediate hyaline cartilage restoration is achieved, bone-to-bone healing of the transferred osteochondral cylinder to the surrounding bone is required and immediate postoperative rehabilitation is dictated by the biology of the bony healing process rather than formation of new repair cartilage tissue.

As an alternative to the use of autologous tissue, osteochondral allografts are used for treatment of large and deep chondral and osteochondral lesions from acute trauma, osteochondritis dissecans, avascular necrosis, and joint degeneration.[15] This technique also provides a hyaline cartilage restoration by using osteochondral grafts obtained from size-matched donor femoral condyles to restore the cartilage defects. This technique can use large-cylinder grafts (Mega-OATS technique) or so-called "shell grafts," which are individually shaped by the surgeon to the specific dimensions of the treated defect and may cover very large osteochondral cartilage defects of 4 to 20 cm^2.

Reparative Cartilage Repair Techniques

Marrow stimulation microfracture is the most frequently used marrow stimulation technique. By micropenetration of the subchondral plate, this technique results in filling the cartilage defect by a blood clot that contains pluripotent marrow-derived mesenchymal stem cells, which subsequently produce a mixed fibrohyaline cartilage repair tissue that contains varying amounts of type II collagen.[124] Second-generation techniques that aim to augment the repair tissue quality and quantity after microfracture have recently been developed.[173] This technique is recommended primarily for smaller cartilage defects of up to 2 to 4 cm^2 in size. Postsurgical rehabilitation must consider that cartilage repair after microfracture occurs in 3 biologic phases: the clot formation phase, repair cartilage formation phase, and cartilage maturation phase.

Chondrocyte-Based Cartilage Repair Techniques ACI is a 2-step procedure. The first step involves an arthroscopic evaluation and cartilage grafting from an area of the joint that has limited weight bearing (usually the intercondylar notch). Chondrocytes are then isolated from the harvested cartilage tissue and cultured with a combination of growth factors to multiply the cells for 3 to 6 weeks. Following in vitro chondrocyte expansion, the chondrocytes are implanted in a secondary open procedure. Implantation into the defect occurs under a periosteal cover that is sutured over the cartilage defect.[18] Matrix-induced autologous chondrocyte implantation is a second-generation technique that uses a biomatrix seeded with chondrocytes and reduces surgical invasiveness and risk for graft hypertrophy.[14] Characterized chondrocyte implantation presents a modification that optimizes hyaline cartilage regeneration through selective expansion of chondrocyte subpopulations characterized by expression of gene marker profiles and phenotypic cell characteristics that have been associated with formation of hyaline cartilage in vivo.[156] These techniques produce a hyaline-like restoration of both small and large full-thickness articular cartilage lesions. A sandwich technique modification with bone grafting can be performed for deep chondral and osteochondral defects. In postsurgical rehabilitation it must be considered that cell-based cartilage restoration involves a cell implantation and stimulation phase, a cell proliferation and matrix production phase, and a matrix maturation phase.

REHABILITATION AFTER ARTICULAR CARTILAGE REPAIR

General Concepts

Rehabilitation following cartilage repair surgery is a critical component of the process of returning the athlete to sports activity. The focus of the rehabilitation program for all articular cartilage repair procedures is to provide a mechanical environment for the local adaptation and remodeling of the repair tissue that will enable the patient to safely return to the optimal level of function. The current concepts of rehabilitation following cartilage repair in the athlete are based on a combination of basic science data, the surgical techniques currently available, empirical information, and a limited number of clinical studies.[5,37,39,45,48,52,62,69,71,72,74,76,92,107,136,147,154,155,190,191] Due to the complex nature of cartilage repair and variable defect characteristics and comorbidities, an individualized rehabilitation approach should be used for every athlete following articular cartilage restoration (**TABLE 1**). The progression through the rehabilitation process is determined by the biology of the repair technique, characteristics of the cartilage injury, clinical symptoms, radiographic findings, and the athlete's sport-specific demand. A thorough understanding of the biological and biomechanical factors to consider and principles of cartilage repair is important. Rehabilitation of an athlete following articular cartilage repair involves a multidisciplinary team approach that requires active and frequent communication. Close communication between surgical and rehabilitation teams is essential for successful recovery and return to sport.

Factors That Influence Rehabilitation

Patients may progress through the rehabilitation process at different rates, depending on individual characteristics, lesion features, and concomitant pathologies (**TABLE 1**).[119] Patient age is a significant predictor of outcomes after articular cartilage repair.[16,119,123] Cartilage repair in older individuals may be slower, due to age-dependent changes in metabolic activity, repair processes, and matrix synthesis.[176,184] Similarly, patients with a body mass index (BMI) greater than 30 kg/m^2 may need slower progression during rehabilitation. Although the relationship between BMI and cartilage repair has not been well established, individuals with BMI greater than 30 kg/m^2 have had worse outcomes after microfracture.[8,125] Higher BMI is also a risk factor for knee osteoarthritis[98,128] and cartilage degeneration[38,44] and is related to decreased cartilage volume.[17,182] Impact sports can result in tremendous biomechanical loads from repetitive joint loading associated with impacts, rapid deceleration, and frequent cutting and pivoting. These sports increase the risk of osteoarthritis and can be detrimental to cartilage repair.[96,153] Kujala et al[88] observed that soccer players and weight lifters had an increased risk of developing premature

TABLE 1 Factors to Consider During Individualized Cartilage Repair Rehabilitation

Considerations/Specific Factors	Implications
Individual	
Athlete's age	Slower cartilage repair with increased age
Body mass index	More gradual rehabilitation progression with body mass index greater than 30 kg/m^2
Type of sport	Higher demand on repair tissue in impact sports
Competitive level	Competitive athletes have better outcomes
Psychological	Less fear of reinjury and higher self-efficacy are associated with better outcomes
Lesion/defect	
Defect size	Smaller defects frequently improve faster with rehabilitation
Repair technique	More rapid rehabilitation progression with restorative techniques
Defect location	Immediate weight bearing for patellofemoral defect (knee brace locked in full extension)
Duration of symptoms	Longer recovery if symptoms persist longer than 12 months (deconditioning)
Cartilage quality	Slower rehabilitation progression with generalized joint chondropenia
Concomitant injuries	
Concomitant procedures	Modified protocols for anterior cruciate ligament reconstruction, meniscal repair, osteotomy, etc
Meniscus status	Slower rehabilitation progression after meniscectomy (especially lateral meniscus)

knee osteoarthritis compared to runners and shooters.[88] Competitive athletes have demonstrated better outcomes than recreational athletes after cartilage repair.[64] Several factors may account for the differences between these groups. Competitive athletes are younger, more motivated to return to sports, and often have better and earlier access to care. After surgery, some patients may reduce their preinjury activity levels for a variety of reasons, including social factors, knee problems, and fear of reinjury.[91,135,183]

Psychosocial factors have been shown to affect return to sport after knee surgery and can be expected to influence rehabilitation and athletic activity after cartilage repair as well.[57,178] Psychological factors that may affect the rehabilitation process include the fear of reinjury (kinesiophobia), coping, emotions, commitment, confidence in performance, and athlete's control of outcome. Useful tools that can be used to evaluate the influence of psychosocial factors on rehabilitation include the Knee Efficacy Scale and the Tampa Scale of Kinesiophobia.[90,178,179] Both the Knee Efficacy Scale and the Tampa Scale of Kinesiophobia have been shown to correlate with outcome measures such as the International Knee Documentation Committee (IKDC) Subjective Knee Form, the Knee Injury and Osteoarthritis Outcome Score (KOOS), and the Tegner-Lysholm Knee Scoring Scale. Higher Tampa Scale of Kinesiophobia scores are associated with failure to return to sport; conversely, higher perceived self-efficacy is related to greater perceived knee function, postoperative sports activity levels, and knee-related quality of life.[23,26,53] Patient education, verbal persuasion, and encouragement during rehabilitation are critical for development of the athlete's self-efficacy. The described stepwise rehabilitation approach with criteria-based progression helps the athlete gradually develop self-confidence by successful goal setting and task completions. Progressive sport-specific tasks may facilitate this positive psychological feedback and development of sport-specific self-efficacy, which may help the athlete to return to athletic activity and performance at the preinjury level.

The characteristics of the cartilage lesion must be considered in the development and implementation of rehabilitation interventions. Smaller lesion sizes typically result in better cartilage repair.[73,104,126] Lesion size and location, the invasive nature of the surgical approach, the specific biological healing responses, and the need to protect the repair site to facilitate proper healing while avoiding deleterious forces are likely to greatly influence the rehabilitation process. The amount of time between injury and surgical treatment may also influence likelihood of returning to sporting activities. Athletes were 3 to 5 times more likely to return to sports if surgery was performed within 1 year of the injury.[124-126] Athletes with generalized joint chondropenia should be progressed slower in rehabilitation to prevent further cartilage breakdown and focal cartilage defects.[34,35]

Concomitant injuries commonly encountered in conjunction with articular cartilage lesions can impact the rehabilitation process. Medial meniscus tears (37%) and anterior cruciate ligament ruptures (36%) are the most common injuries concomitant with articular cartilage injuries.[185] Correcting these combined injuries is crucial in the success of cartilage repair.[104,113] Recent studies have demonstrated that combined procedures (anterior cruciate ligament reconstruction, high tibial osteotomy, and meniscal allograft and repair) did not adversely affect return-to-sport rate after cartilage repair and even improved outcomes.[83,125,170] However, rehabilitation progression should be slower following meniscectomy, especially of the lateral meniscus.[3,108] Therefore, treatment guidelines may need to be modified to accommodate the healing characteristics of the other biological tissues concomitantly addressed during surgery.

Return to Sport After Knee Articular Cartilage Repair

Current surgical and rehabilitation techniques have demonstrated encouraging results in pain reduction and functional improvement. A primary goal for many athletes after articular cartilage repair is to return to their previous level of sports participation, while reducing the risk of reinjury. Surgical technique, patient factors, and concomitant injuries can influence the rate of return to sport after cartilage restoration.[118,119] Return to competition was demonstrated in 59% to 66% (range, 25%-100%) of athletes after microfracture, with 57% returning to their preoperative performance level.[64,118,120,126] Successful return to athletic activity was reported in 91% to 93% (range, 86%-94%) of athletes after OATS as early as 6 to 9 months postoperatively.[61,64,83,103] A recent study demonstrated that 84% of athletes returned to sport after osteochondral allograft transplantation, with 60% returning to their preinjury performance level.[150] Several prospective studies have shown the ability to return to sport in 33% to 96% of athletes after ACI, with 60% to 80% of them returning to the same skill level.[119,121,122] Irrespective of the technique used for cartilage repair, the rate for return to sports was higher for younger and more competitive athletes with preoperative duration of symptoms of less than 1 year (**TABLE 1**).[64] Microfracture and OATS were effective primarily in athletes with smaller lesions, while the ability to return to sport after chondrocyte transplantation was independent of lesion size. While some studies reported decreasing function starting 2 years after microfracture and OATS, no similar functional decline was observed for ACI.[119] Postoperative participation in sports improved the long-term functional results after ACI.[32,86,180] The timing of return to sports varies from 7 to 18 months, depending on the surgical technique. Average time to return to sport was longest for ACI (18-25 months) and shortest for OATS (6.5-7 months).[64,119] Athletes were able to return to sports 8 to 17 months after microfracture.[64,126] The biology of these cartilage repair techniques may explain this chronological difference, which emphasizes the principle of individualized technique- and athlete-specific progression of postoperative rehabilitation. To ensure optimal care, the rehabilitation team should be familiar with the surgical and biological principles that determine the protection of the postoperative joint and apply them for each individual athlete's unique set of circumstances.

TABLE 2 BIOLOGIC AND REHABILITATION PHASES AFTER ARTICULAR CARTILAGE REPAIR

	Biologic Phase	Rehabilitation Phase
Phase 1	Graft integration and stimulation	Protection and joint activation
Phase 2	Matrix production and organization	Progressive loading and functional joint restoration
Phase 3	Repair cartilage maturation and adaptation	Activity restoration

TABLE 3 EXAMPLES OF THERAPEUTIC INTERVENTIONS AND PROGRESSIONS IN EACH PHASE

Phase/Aims	Therapeutic Intervention
Phase 1	
Protection and joint activation	• Preoperative counseling • Cryotherapy, elevation, and compression • Continuous passive motion • Patellar mobilizations, all directions, but take care with patellofemoral repairs • Weight-shift exercises for weight-bearing control training • Gait training within weight-bearing restrictions • Active-assisted heel slide exercises progressing to gradual increases in pain-free active knee ROM exercises (patellar/trochlear defects have slower progression in ROM than femoral defects) • Stationary cycle • Stationary cycle, minimal resistance once 100° of knee flexion are achieved • Full active ROM exercises for ankle and hip • Quadriceps setting exercises progressing to multi-angle isometric exercises • Biofeedback and NMES • Partial weight-bearing proprioceptive exercises (not greater than weight-bearing restrictions) • Gluteal muscle retraining • Aquatic therapy introduced once surgical incision has healed • Rowing ergometer, no resistance (no handle) • Introduce treadmill walking after full weight bearing • Introduce forward lunges, forward step-ups, and lateral step-ups within safe range of knee flexion after full weight bearing • Stretching program

Table continued on page 259.

Rehabilitation Phases

Independent of the inherent differences between cartilage repair techniques, the process of rehabilitation and returning the athlete to sport after knee articular cartilage repair is based on, and consists of, 3 biological healing phases: an initial protection and joint activation phase, followed by a progressive joint loading and functional restoration phase, and finally an activity restoration phase (**TABLES 2** and **3**). The development and implementation of these treatment guidelines reflect a criteria-based ap-

TABLE 3 Examples of Therapeutic Interventions and Progressions in Each Phase (continued)

Phase/Aims	Therapeutic Intervention
Phase 2	
Progressive joint loading and functional restoration	• Continue quadriceps NMES until greater than 80% side-to-side quadriceps strength is achieved • Progress knee exercises to light resistance within safe ranges, with no resistance over repaired zone • Progress from concentric to eccentric loading • Progress from static to dynamic loading • Gluteal, posterior hip, and lateral hip-strengthening exercises • Proprioception/balance exercise progressions: stable to unstable surfaces, uniplanar to multiplanar, double- to single-limb • Progress proprioception exercises to more challenging surfaces and introduce coordination and sport-specific tasks • Introduce low-impact uniplanar aerobic activities and progress to moderate-impact uniplanar activities and then to multiplanar activities • Introduce plyometrics in supine double-limb landing with gravity eliminated, progressing to single-limb landing with gravity eliminated and then to standing on foam surface • Continue patellar mobilizations and introduce joint mobilizations of hip, knee, and tibiofibular joints • Soft tissue mobilization of the iliotibial band, patellar and quadriceps tendons, popliteal space, and proximal hip • Continue cycle and rowing ergometer with increasing duration and gradual increase in resistance • Continue aquatic therapy for general endurance • Continue stretching program
Phase 3	
Activity restoration (sport-specific reconditioning/on-field rehabilitation)	• Restoration of symmetry, strength, and flexibility in lower limb • Loading program individualized with progression to full resistance over repaired defect in both closed-kinetic-chain and open-kinetic-chain activities • Functional sport-specific agility training • Presport cardiovascular conditioning • Increase intensity and duration of exercise • Continue strengthening and flexibility exercises from phase 2 • Education and preparation for return to sport

Abbreviations: NMES, neuromuscular electrical stimulation; ROM, range of motion

proach based on scientific research of articular cartilage repair healing constraints, knee complex biomechanics, neuromuscular physiology, and general sport-specific tasks. Thus, progression through rehabilitation should be based on criteria rather than fixed time lines (**TABLE 4**). However, the implementation of discretely different surgical techniques can influence the biomechanical and physiological function of the cartilage, which demands careful attention to its specific healing constraints.

The therapist must monitor any progressions in exercise and activity to ensure that symptoms are not increased. Pain and swelling are primary indicators that rehabilitation is progressing too rapidly and overloading the healing tissue.[9] Grading of the effusion with the modified stroke test and soreness rules provide clinicians with reliable methods for symptom monitoring and progression of exercises and activity.[103,174] A home exercise program should be developed based on affordability and accessibility to ensure full compliance with the exercise prescription.

Phase 1: Protection and Joint Activation Factors related to the function of the knee prior to surgery are important in expected and final outcomes after surgery.[29,40,85,97] Preoperative patient counseling and education, along with preoperative correction of overt impairments such as muscular imbalances or deficits, will help to facilitate postoperative progression through the individual steps of the rehabilitation process. In addition, gathering information about the athlete's occupational and athletic demands and access to rehabilitation facilities and modalities is extremely useful in designing the optimal rehabilitation program.

The biology of the healing process in the first phase differs between restorative and reparative techniques. With reparative techniques, the cells contained in the defect (mesenchymal stem cells or chondrocytes) start differentiating and producing a primitive, unorganized, and soft initial repair cartilage tissue. During this phase, the soft, putty-like repair tissue is vulnerable to mechanical overload and requires protection to avoid limited integration of the repair tissue to the defect base and surrounding normal articular cartilage.[158,165] In contrast, for restorative repair techniques such as osteochondral allograft or autograft, initial protection is aimed to allow for adequate bone-to-bone healing of the implanted grafts. Because these techniques rely on bony healing as opposed to cartilage growth, progression of weight bearing is usually faster with restorative techniques. High compressive and shear stresses during the first rehabilitation phase can decrease chondrocyte metabolic rate, thereby negatively affect the process of repair tissue and integration for both reparative and restorative techniques.[127] In contrast, low mechanical forces may promote cartilage formation and nutrition, as well as

TABLE 4 Weight-Bearing Guidelines and Criteria for Progression After Articular Cartilage Repair

Phase 1. Weight-Bearing Guidelines

- Femoral defects
  - Restorative techniques (OATS/allograft): touch-down loading for 2 wk, then progress to full weight bearing by 4 to 6 wk
  - Reparative techniques (microfracture/ACI): touch-down loading for 2 wk, then progress by 25% body weight per wk
- Patellar/trochlear defects
  - Immediate weight bearing with brace locked in 0° to 10° of knee flexion

Progression Criteria to Go from Phase 1 to Phase 2

- Full passive ROM equal to the nonoperated knee
- Minimal or absent pain (VAS less than 3/10)
- Minimal or no effusion (grade 0 or 1+)
- Recovery of muscular activation
- Recovery of normal gait cycle (equal stride length and stance time between limbs, no limp)

Progression Criteria to Go from Phase 2 to Phase 3

- Full and painless ROM
- No or minimal pain (VAS less than 3/10)
- No or minimal effusion (grade 0 or 1+)
- Maximum peak torque difference of less than 20% between limbs on isokinetic test
- Hop performance difference of less than 10% between limbs
- Self-report outcomes greater than 90%
- Ability to run on a treadmill at 8 km/h for more than 10 min
- MRI evaluation of the repaired cartilage to evaluate repair tissue

Abbreviations: ACI, autologous chondrocyte implantation; MRI, magnetic resonance imaging; OATS, osteochondral autograft transplantation system; ROM, range of motion; VAS, visual analog scale

bone-to-bone healing.[7,71,92] In the early postoperative phase, the challenge is to construct an individualized rehabilitation program that provides appropriate stimulation, while avoiding mechanical loading that may be detrimental to the repair tissue. Due to the differences introduced by different cartilage repair techniques, lesion characteristics, and concomitant procedures, the initial limit and progression of weight-bearing activities should be individually determined by the surgical and rehabilitation teams for each athlete. Consequently, the duration and activities of the protection phase may be variable. The focus during the first phase of an articular cartilage repair program should be on reducing pain and effusion, monitoring weight-bearing restrictions, and addressing impaired range of motion (ROM), muscle performance, and neuromuscular control.[62,72,78,147]

The scientific and clinical evidence to directly support the frequency, intensity, type, and timing of exercises and other therapeutic modalities for articular cartilage repair rehabilitation is limited.[32,62,76,119,147,180,190] The incorporation of therapeutic modalities and exercises into an articular cartilage repair rehabilitation program is best conceptualized in terms of optimizing joint stress, as opposed to the complete avoidance of specific ranges of movement. This can be achieved through the selection, introduction, and progression of exercises that are appropriate for the repair tissue status, size, and location. The repair site is most vulnerable during the initial phase after articular cartilage repair, and a graded rehabilitation program that incorporates preoperative counseling, progressive weight bearing, and controlled exercise is recommended during the initial protection and joint activation phase. A thorough understanding of the applied clinical biomechanics and an appreciation of forces and loads exerted on the developing graft tissue are essential for designing the appropriate rehabilitation program during this phase. If concomitant surgical procedures, such as anterior cruciate ligament reconstruction, meniscus repair, or osteotomy, are performed, the rehabilitation program should be revised on an individual basis by incorporating the requirements of the concomitant procedure in conjunction with the articular cartilage repair requirements.

Pain and Effusion After knee surgery, patients frequently have complaints of pain and knee joint effusion. Decreased voluntary activation of the quadriceps and altered knee joint mechanics have been associated with experimentally induced effusion.[137,138,168] The reduction of pain and knee joint effusion is a primary goal initially after cartilage repair, with cryotherapy being an effective modality that clinicians and patients can readily use. The application of cryotherapy (**FIGURE 1**), compression, and elevation is important to lower tissue temperature, slow metabolism, decrease secondary hypoxic injury, and reduce edema formation.[102] A meta-analysis by Raynor et al[146] demonstrated that patients who received cryotherapy had less postoperative pain but no improvement in early ROM after anterior cruciate ligament reconstruction. The use of compression wraps or a sleeve may also assist in the reduction of effusion.

Pain and particularly joint effusion following exercise should be avoided, as these may lead to quadriceps inhibition and its negative effect on neuromuscular joint control, joint biomechanics, and resultant increase in joint reaction force in the area of the cartilage repair.[97] While mild to trace joint effusion may be normal during the first 4 to 6 weeks after articular cartilage repair, extensive efforts should be made to limit and reduce effusion by avoiding overly aggressive rehabilitation. Recurrent joint effusion indicates overload of the repair cartilage and premature progression during rehabilitation and should be avoided.

Weight-Bearing Restrictions Load-induced formation and remodeling of the articular repair tissue is an important component of rehabilitation that starts in phase 1. The scientific and clinical evidence to determine the optimal timing of return to full weight bearing following articular cartilage repair is increasing but varies across different types of articular cartilage repair procedures.[32,58,119,125,147,170] In addition to the surgical technique, the amount of initial weight bearing and progression should be individually determined based on articular lesion and patient characteristics and associated surgical procedures (**TABLE 4**). Cell-based articular cartilage repair procedures have historically included the longest periods of weight-bearing restrictions.[62] Newly emerging research indicates that it is possible to accelerate weight-bearing loads in certain patient populations and have good clinical and functional outcomes without jeopardizing the graft.[37,190] While initial guidelines emphasized the importance of minimizing shear stress in the early stages of rehabilitation after cartilage repair, recent research has shown that moderate dynamic compression and low shear loading are beneficial to extracellular matrix biosynthesis, chondrocyte proliferation, and repair tissue maturation, while static compression and immobilization are associated with adverse effects.[7,71,92] However, high shear stress may lead to mechanical failure of articular cartilage repair in the early postoperative rehabilitation phase; it is therefore necessary to implement a graded increase of joint stresses and loading. Weight-bearing status should be based on the location of the repair on the tibiofemoral and patellofemoral joint surfaces. It is important to recognize that patients do not reliably maintain their weight-bearing restrictions. The accuracy of weight-bearing application can be assessed, taught, and reinforced with patients both presurgery and postsurgery, using 2 identical scales (**FIGURE 2**).[62] This technique is also useful for controlling weight-shift exercises and for correction of body posture and any residual unloading of the involved limb later in the rehabilitation process. Because normal arthrokinematics during dynamic athletic activities involve rolling, spinning, and gliding motions of the knee joint, early restoration of joint kinematics is an important goal of the first rehabilitation phase. Restoration of normal arthrokinematics will also help maintain repair cartilage homeostasis in the later stages of rehabilitation.[48,52,92] Gait training focuses on crutch walking to minimize soft tissue restrictions (especially tightness in hamstrings, gastrocnemius, and soleus muscles) and increase load acceptance on the involved limb through controlled weight shifting.

FIGURE 1. Cryotherapy.

FIGURE 2. Weight-bearing progression.

Aquatic therapy can start once the surgical incision has healed and the patient is able to safely transfer in and out of the pool. Water depth used for the exercises should reflect the current weight-bearing status of the individual.[65] Although no evidence-based consensus currently exists on the use of postoperative bracing after knee articular cartilage repair, a brace locked in full extension is commonly recommended for patellofemoral repairs for the first 4 to 6 weeks, especially if the defects are large, kissing, or if there is an active quadriceps extension lag.

FIGURE 3. Continuous passive motion.

Impaired ROM Restoration of normal ROM presents a critical initial step toward normalization of joint kinematics. Repetitive dynamic movement through the available ROM provides mechanical stimulation to chondrocytes and increases synovial fluid flow and graft nutrition.[74,190] Continuous passive motion (CPM) is recommended immediately postoperatively and is a standard inclusion in articular cartilage repair rehabilitation in many centers (**FIGURE 3**).[72] In addition to its effect on ROM, CPM is reported to increase the quality of chondral repair tissue and stimulate the metabolism of proteoglycan (PRG4).[4,136,154,155] The current recommendation for the use of CPM is based on basic science, empirical practice, case series, and disease-oriented evidence.[72] A retrospective study by Rodrigo et al[151] indicated that following microfracture surgery, patients who used a CPM device were more likely to have improvement in cartilage healing on second-look arthroscopy compared to those who did not use a CPM device. Based on available evidence, CPM use is recommended for 4 to 6 weeks postoperatively to stimulate the cellular response in the implanted graft and neomatrix production.[151,154,189] Once again, individualized restoration of ROM and CPM use should be based on articular defect and patient characteristics. Following patellofemoral chondral repairs, the progression of ROM with CPM should be slower than that following tibiofemoral chondral repairs, because of the high joint reaction stress in the patellofemoral joint during passive knee flexion ROM.[120] CPM is not consistently used across cartilage repair centers and is often not available to patients. Some studies have indicated that for patients with small, isolated defects of the femoral condyle and intact surrounding cartilage, CPM may be replaced with graded weight bearing and active ROM. However, these studies had small cohorts or were case reports with a low level of evidence, the outcomes of which cannot be generally extrapolated.[5,107] Where CPM is not available, it may be substituted by 500 active-assisted heel slides, performed 3 times per day, with the same ROM progressions and goals indicated for CPM.[62] Stationary cycling with partial revolutions can be initiated to promote ROM. Once knee flexion ROM is 95° to 100°, full-revolution cycling with minimal resistance can be introduced (**FIGURE 4**).[62] ROM exercises should progress through a controlled increase in motion through passive, active-assisted, and then active movements. Active ROM exercises can be progressed to light resistance in safe ranges, while simultaneously maintaining no resistance over the repaired area. Safe ranges will be dictated by the articulation surfaces, contact area, and size and location of the graft (**FIGURE 5**). For example, as the posterior aspect of the medial femoral condyle contacts the tibia between 90° and 120° of knee flexion, light resistance in the range of 0° to 80° of knee flexion may be appropriate if the articular defect was on the posterior aspect of the femoral condyle.[76] Several articles provide detailed information on the clinical biomechanics of the tibiofemoral and patellofemoral joints.[39,59,114]

Knee motion loss can be a disabling complication. Arthrofibrosis is a common cause of knee motion loss after knee surgery.[142,163] Patients with limited knee motion due to arthrofibrosis often complain of anterior knee pain, swelling after prolonged positions or activity, quadriceps weakness, and joint stiffness, which can result in decreased tolerance to stand, walk, or run, and difficulty returning to previous levels of activity.[112,140,159,161] Additionally, increases in patellofemoral contact pressure have been documented in knees with quadriceps or patellar tendon adhesions.[2] Therefore, the use of patellar mobilizations should be a part of any early postoperative treatment. In the early postoperative period, gentle patellar mobilizations in all directions 4 to 6 times per day are important to prevent adhesions and arthrofibrosis (**FIGURE 6**).[28]

FIGURE 4. Stationary cycling.

Impaired Muscle Performance Following the surgical trauma, early muscular activation is an essential component of restoring muscular joint control and normal arthrokinematics. The use of isometric muscle dynamometry allows the clinician to track the progress of muscle performance throughout the recovery period. Isometric testing, if the location and size of the cartilage repair are known, may be performed early after surgery to avoid testing positions that may increase joint stress and thereby damage the cartilage repair. This testing consists of maximal isometric voluntary contraction (MVIC) of the quadriceps and hamstrings. To produce an MVIC, patients are familiarized with the testing procedure and provided with standardized verbal encouragement from the therapist and visual feedback from the dynamometer's real-time visual display. Patients perform three 5-second MVICs, each separated by a 2-minute interval to allow the muscles to rest and to avoid fatigue. The side-to-side percent deficits in the MVIC for the knee extensor and flexor muscles are then calculated.

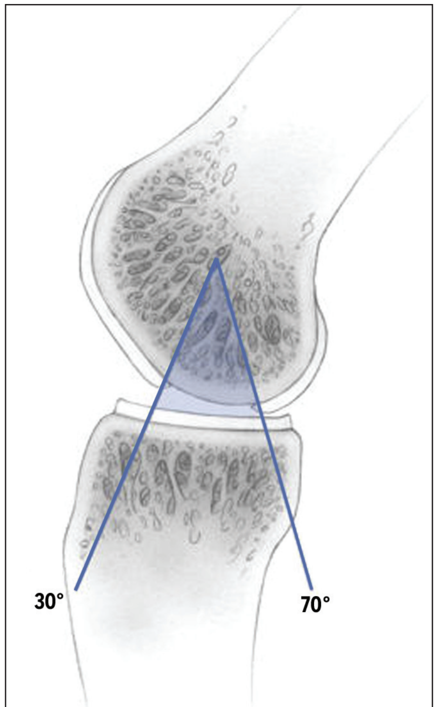

FIGURE 5. Schematic drawing illustrating the unsafe range of motion during which the cartilage defect articulates with the opposing joint surface (from Mithoefer et al[124]).

Quadriceps strength deficits are frequently observed after knee surgery and may persist.[25,29,138] Isometric quadriceps setting exercises are performed and progressed from full knee extension position to multi-angle exercises. In patients with gross quadriceps strength deficits, neuromuscular electrical stimulation (NMES) may help to promote quadriceps strength gains. NMES can be introduced early during the postoperative period and is a valuable adjunct to the program, especially when voluntary control of the quadriceps mechanism is still impaired (**FIGURE 7**). The use of NMES combined with exercise has been shown to be effective in treating quadriceps strength deficits after anterior cruciate ligament reconstruction.[82,192] NMES can improve quadriceps strength if applied at a high-intensity setting early in the rehabilitation process.[30,99,166] Quadriceps

FIGURE 6. Patellar mobilization.

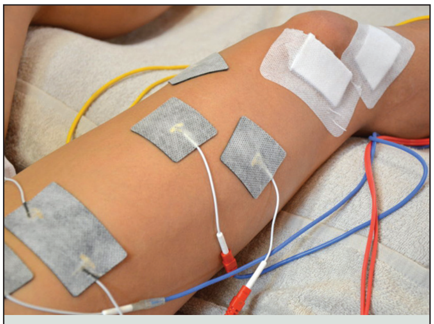

FIGURE 7. Neuromuscular electrical stimulation.

strength deficits should be within 30% of the contralateral limb with isometric dynamometry to progress to phase 2 of rehabilitation.

Once full weight bearing has been restored, weight-bearing (closed-chain) exercises can be introduced within safe ranges, as dictated by the repair location and size. During this phase, weight-bearing exercises must be gradually introduced to facilitate healing and to reduce postsurgical complications. During weight-bearing movements, all condylar surfaces bear weight through the arc of knee motion.[177] With weight-bearing movements, tibiofemoral joint contact forces progressively increase with knee flexion to reach 2.7 to 4 times body weight at 90° of flexion. Similarly, patellofemoral contact forces progressively increase with knee flexion to reach 6.5 to 9 times body weight at 90° of flexion.[1,42] Patients can safely begin to incorporate weight-bearing exercises, such as forward lunges and forward and lateral step-ups, from 0° to 60° of knee flexion as long as substantial compressive loads to the healing articular cartilage do not occur. Prior to initiating these functional exercises, patients need to demonstrate adequate strength and neuromuscular control to properly perform the exercises. Proper technique must be maintained throughout the exercises.

Impaired Neuromuscular Control In addition to weight bearing, CPM, and ROM guidance, rehabilitation guidelines should provide information regarding neuromuscular control and re-education. Alterations in neuromuscular control may influence clinical outcomes.[75,149] Knee surgery results in proprioceptive deficits that should be addressed at the earliest postoperative opportunity.[69] Proprioceptive training can be initiated in the early phase of rehabilitation within the patient's weight-bearing restrictions. This may often require adaptation of exercises to match the weight-bearing restrictions and can be progressed along with increased weight-bearing status.

Impairments of the gluteal muscles can influence tibiofemoral and patellofemoral joint biomechanics. Gluteus maximus and medius play an important role in the neuromuscular control of dynamic valgus of the knee and, consequently, normal posture and gait patterns.[10,144,164] Therefore, gluteal muscle retraining is an important component of articular cartilage repair rehabilitation, especially when patients have altered lower extremity kinematics.[145]

Milestones for Phase 1 Milestone criteria for advancement to phase 2 (**TABLE 3**) include full passive extension and flexion ROM equal to the nonoperated knee, minimal to no pain (less than 3/10 on a visual analog scale), minimal to no effusion (grade 0 or 1+), ability to perform active straight leg raises without a quadriceps extension lag, side-to-side deficits of quadriceps strength of less than 30%, and ambulation with equal stride length and stance time between limbs and full knee extension at heel strike. Once the objectives of the protection phase have been achieved, the patient may be progressed to the second phase of cartilage repair rehabilitation.

FIGURE 8. Isokinetic muscle strength test.

Phase 2: Progressive Joint Loading and Functional Restoration The focus of the second phase is to begin controlled gradual increase of the mechanical stress on the primary repair tissue to stimulate cellular metabolism leading to production of proteoglycans and collagen deposition.[171] This controlled stimulus to the healing cartilage is gradually applied while preventing excessive overloading that might damage the repair. This allows the cartilage repair tissue to strengthen and become more resilient to increasing mechanical stress and more complex joint loading patterns, including both compressive and shear forces. This phase of rehabilitation is, therefore, designed to maintain ROM and flexibility, while restoring neuromuscular control and initiating simple sport-specific movement patterns. The clinical focus for the second rehabilitation phase is directed toward addressing altered joint loading and impaired lower extremity muscle performance, neuromuscular control/dynamic balance, and sport-specific movement patterns while maintaining full active ROM without pain, effusion, or locking.

Impaired Muscle Performance Emphasis is placed on full restoration of strength and balance to address residual deficiencies. Strength deficits in the quadriceps and hamstrings, as well as quadriceps-to-hamstrings strength imbalance, should be actively addressed. Testing can be performed with an isokinetic device (**FIGURE 8**) after adequate practice is allowed to ensure maximal effort. After warm-up exercises, the patient is asked to perform 4 maximal concentric repetitions (ROM from 0° to 90°) at a speed of 90°/s. A side-to-side deficit in quadriceps strength greater than 20% is an indicator of poor quadriceps strength[97,162] and should continue to be treated with NMES.[167] Electrical muscle stimulation and/or biofeedback should also be continued if significant atrophy or muscle inhibition is noted.[147] By the end of phase 2 and before proceeding to phase 3 of the rehabilitation, patients should demonstrate less than 20% side-to-side strength deficits for knee flexion and extension when tested at 90°/s.

For patients who continue to exhibit strength deficits, the use of non–weight-bearing (open-chain) exercises has been shown to be effective in enhancing muscle strength after knee surgery.[21,111,116,172,175] With non–weight-bearing movements, tibiofemoral joint compressive forces decrease with knee flexion.[186,193] Patellofemoral contact forces progressively increase with knee flexion once loads exceed 25 N.[27] Proper technique must be maintained throughout the performance of exercises and no increase in symptoms should occur.

Athletes must be able to decelerate their body or a body segment rapidly to successfully complete sports maneuvers. During deceleration, the lower extremity muscles absorb mechanical work while lengthening.[93] Eccentric muscle training is effective in enhancing quadriceps strength and hop performance after anterior cruciate ligament reconstruction.[54,55] Submaximal eccentric muscle-loading exercises may assist in overcoming force attenuation impairments.[93] We recommend that athletes demonstrate peak eccentric torque symmetry within 20% of the opposite side when tested at 90°/s.

Deficits in hip abduction torques have been associated with excessive lower extremity dynamic valgus and anterior cruciate ligament injuries in female athletes.[51,68] Hip strength asymmetries in athletes may also result in suboptimal performance on the playing field and have been linked to an increased risk of second anterior cruciate ligament injury.[12,68,133,139,160] Restoring optimal gluteal, posterior hip, and lateral hip strength and control is important if any dynamic valgus or excessive lateral compartment loading at the knee is recognized. Patients should demonstrate no more than a 15% side-to-side deficit in hip abduction strength at the end of phase 2.

FIGURE 9. Proprioceptive exercises.

Impaired Neuromuscular Control/Dynamic Balance In the second phase, the restoration of neuromuscular control is critical to optimize joint function and return to athletic activity. The entire kinetic chain of the lower extremity (hip, thigh, and calf) and trunk musculature should be addressed. Proprioception, dynamic joint stability, reactive neuromuscular control, and functional motor patterns are affected by knee injury.[11,13,20,95,188] The role of rehabilitation is to enhance the function of the sensorimotor system to integrate and process mechanoreceptor information, creating synchronized and synergistic motor responses that reduce microtrauma and recurrent injury on joint structures.[57,96,155] Balance activities should progress from bilateral to unilateral stance, eyes-open to eyes-closed exercises, stable to unstable surfaces, slow to fast speeds, unidirectional to multidirectional movements, and simple to complex skills (**FIGURE 9**).[79,155,156,158] Balance activities are progressed when patients are able to maintain their limb, joint, and body position while reacting and adapting to changes in loads and forces.[133] Myer et al[133] recommended that patients be able to maintain postural control for at least 5 seconds during a single-limb squat performed at 60° of knee flexion. The inability to maintain postural control may amplify limb-to-limb strength deficits during functional tasks.

After adequate strength and postural control have been achieved, the use of perturbation devices is indicated to further enhance neuromuscular control. Perturbation of the support surface by the rehabilitation specialist is performed to alter forces and torques in multiple planes in a systematic progression.[46] The patient's objective is to either resist the force applied by the therapist or to re-establish a balance posture after the perturbation was applied. A progression in difficulty, similar to the one described above for balance activities, can be followed. Subsequent sessions progress from expected to random directions and timing of the perturbation, increasing intensity and magnitude of the forces, and decreasing verbal cues. Progression of perturbations is individualized based on the patient's ability to apply appropriate directional and counter-resistive force and muscle activation patterns and reduction in loss of balance.

Having the patient perform various functional tasks while standing on an unstable surface should follow and should progress by increasing the difficulty of the tasks. Providing verbal, tactile, and visual cues is indicated initially but should be strategically and systematically removed when the patient is able to adapt and react to the perturbation. A rehabilitation program augmented with perturbation training has been shown to result in improvements in physical performance measures, self-report outcomes, and biomechanical deficits.[22,41,46,66] Perturbation training is an effective training approach to improve dynamic knee stability in athletes and patients following anterior cruciate ligament injury. Neuromuscular and proprioceptive re-education has important implications for dynamic joint alignment and has been shown to play an important role in preventing injury or reinjury.[105,132]

Altered Joint Loading Patients who desire to return to a high-level sport or an activity that requires jumping and landing should initiate plyometric activities during this phase. While the effects of plyometric training on patients recovering from knee injuries, especially after articular cartilage repair, are unknown, it may be a critical training method to safely return athletes to full sports participation.[24,60,70,81,87,94,110,120,130,131] Because of the considerable loads and speeds applied to the healing joint with plyometric training, patients should first demonstrate the ability to tolerate the demands of daily activities without pain or swelling.[24] Clinicians must be diligent in monitoring the patient's response to training, using effusion grading and soreness rules. Additionally, the clinician should stress that patients maintain proper technique throughout the plyometric training. It is critical to include the work-rest time ratios (1:1 or 1:2) recommended during this phase of rehabilitation, and plyometric training should not be performed on successive days.[24] Volume, intensity, duration, and frequency of training should not be progressed if patients exhibit poor technique, fatigue, or are unsafe during the performance of the task. Chmielewski et al[24] recommended that volume be increased prior to increasing the intensity or frequency of exercise or decreasing rest time. The use of orthotics, bracing, and taping can be helpful during this phase, potentially to reduce the compressive and shear loads in the compartment where the repair has occurred.

We recommend that plyometric exercises be performed first in a supine position (gravity eliminated), using double-limb landing to initially minimize the stress applied to the joint. The emphasis should be on achieving equal load sharing across the entire joint surface and between limbs. If poor technique is exhibited by the athlete, such as excessive internal rotation of the femur, external rotation of the tibiofemoral joint, excessive foot pronation, or excessive dynamic knee valgus, it is critical to address the movement dysfunction at this point in time, prior to introducing single-limb landing or exercises against gravity. Once the athlete demonstrates proper technique and is able to tolerate the volume and intensity prescribed without pain or swelling, plyometrics can be performed using a single limb but in a supine, gravity-eliminated position. Standing plyometrics should be introduced and performed initially on foam or other forgiving/compliant surfaces to minimize the applied and functional forces being generated. Plyometric exercises can effectively restore neuromuscular joint control to optimize joint biomechanics and load distribution under higher impact conditions, with the goal of protecting the repair cartilage from overload.

Impaired Sport-Specific Movement Patterns The resumption of low-impact activities is recommended based on the athlete's preferred sport and the surgical approach. Low-load activities produce tibiofemoral joint loads between 1.2 times body weight with cycling and 6 times body weight with stair descent,[89] and patellofemoral joint loads between 0.5 times body weight with level walking and 5.7 times body weight with stair descent.[157] Low-load activities, such as skating, rollerblading, and cross-country skiing, can be initiated when the patient has full knee ROM, no pain or effusion with weight-bearing activities, and sufficient healing of the repaired cartilage. Subsequent gradual progression to moderate-impact activities (jogging) occurs when the athlete has side-to-side quadriceps strength greater than 80% and ambulates with a normal gait pattern. Patients are permitted to begin a walk/jog progression program on a treadmill to augment unilateral limb strengthening and force generation and attenuation during the dynamic component of running.[103] The running progression begins with alternating jogging and walking for a distance of 3.2 km. The ratio of run-to-walk distance is initially gradually increased before increasing the running distance to the patient's preferred or required amount.

Maintenance of ROM/Flexibility It is important to continue to include manual therapy in this phase of treatment. Joint mobilization of the patella, hip, and tibiofemoral and tibiofibular joints may be indicated at this time. Deyle et al[33] utilized a combined rehabilitation program of manual therapy techniques and standardized knee exercises to improve 6-minute walk time and self-report scores in patients with knee osteoarthritis. Soft tissue mobilization of the iliotibial band, patellar and quadriceps tendons, popliteal space, and the hip region should be included. A randomized controlled trial in patients with knee osteoarthritis has demonstrated improvements in self-report scores, pain, ROM, and functional performance after an 8-week program of massage therapy.[141] The patient should be educated in monitoring joint stiffness and instructed to mobilize joints and soft tissues and to actively treat any acute effusion as a result of the introduction of new therapeutic activities.

Milestones for Progression to Phase 3 The athlete can progress to on-field rehabilitation when the following criteria are met: full ROM, minimal or no pain (visual analog scale less than 3/10), minimal or no effusion (grade 0 or 1+), less than a 20% side-to-side deficit in maximal peak torque tested with an isokinetic device,[167,187] less than 10% side-to-side deficits on 4 single-leg hop tests (single hop for distance, crossover hop for distance, triple hop for distance, and 6-meter timed hop),[47,67,134,148] and the ability to run on a treadmill at 8 km/h for more than 10 minutes.[32,133,152,174] Additionally, patients should demonstrate scores greater than

TABLE 5 On-Field Phases

Stage	Test	Rehabilitative Exercises
1	• Aerobic fitness test	• Gaining confidence with the environment and the ground • Walking in a straight line without shoes • Circular walking • Slow running in a straight line on rehabilitation field • Exercises of mobilization and coordination • Sand exercises (walking, balancing without jumping)
2		• Circular running • Skipping exercises • Increasing speed of running • Light jumps and landings on the sand • Advanced proprioceptive exercises • Aerobic conditioning
3	• Countermovement jump • Squat jump	• Running at different speeds with slow changes of direction • Slow decelerations • Skips (different patterns) • Jumps and landings on the field • Aerobic conditioning
4		• Running with fast changes of direction • Decelerations • Technical and sport-specific exercises • Jumps and landings with rotations • Aerobic conditioning • Anaerobic-threshold running for 15 min
5	• Aerobic fitness test • Countermovement jump • Squat jump	• Sprinting and fast changes of direction • High-intensity exercises in playing situations • Aerobic conditioning • Anaerobic-threshold running for 20 min

90% on the Knee Outcome Survey activities of daily living scale (KOS-ADLS) and the global rating scale of perceived function.[46,67] Athletes not meeting these criteria should continue rehabilitation with a focus on the areas in which they did not achieve the milestones. By using objective criteria rather than fixed time tables, this strategy for progression to on-field rehabilitation follows one of the main principles of sports rehabilitation.[90]

As the athlete moves to the next phase of the treatment, on-field rehabilitation, open and continued communication among the rehabilitation team, coaches, and training staff is crucial to achieve the optimal outcome for the athlete.

Phase 3: Activity Restoration In addition to the physical criteria listed earlier, cartilage-sensitive MRI evaluation of the graft or repair tissue is routinely recommended to determine the status of the graft before advancing to on-field rehabilitation and high-impact athletic activities. MRI is helpful to evaluate the volume of the repair cartilage and can help rule out significant graft hypertrophy or subchondral bone marrow edema, which may indicate risk of graft failure or graft delamination. Increased risk for traumatic graft delamination has been observed in high-impact athletes with graft hypertrophy after first-generation chondrocyte implantation.[122] Newer MRI techniques, such as d-GEMRIC and T2 mapping, also provide qualitative information about the repair tissue that can help with the individualized progression of the on-field rehabilitation.

On-field rehabilitation is the final and important component of the return-to-sport program following cartilage repair. During this phase, further organization and maturation of the cartilage repair tissue is expected through adaptation to the increasingly more demanding joint stresses associated with impact and pivoting activities. Adaptations include increased rigidity of the matrix due to further proteoglycan deposition and cross-linking, collagen production, and cellular orientation and organization within the neocartilage tissue.[176,184] Gradually increasing impact and sport-specific movement patterns during this phase is intended to prepare the athlete to return to the high mechanical stresses associated with sports, without overloading the repair tissue, which could potentially lead to repair tissue deterioration. Currently, it is not known how the repair tissue quality affects joint function and ability to return to sport; however, limited repair tissue volume has been associated with a higher failure rate.[126]

The final phase is to develop a program that allows for continued recovery while progressively replicating and simulating the complex interaction of tasks during sports.[31,101] Rehabilitation specialists must understand the needs of the athlete and design an appropriate program to eventually meet the biomechanical and physiological demands of their sport. The goal is to progressively challenge the athlete to allow for full clearance for integration back to physical or sporting activities, while minimizing the risk of reinjury. The primary goal of this last phase of rehabilitation is to address any remaining impairments in muscle power, metabolic capacity, and sport-specific movement patterns, as well as diminished athletic performance.

The on-field rehabilitation phase should follow a continuum, building on activities used to simulate athletic movement patterns that were started during the late stages of the second phase of rehabilitation and were taking place in the

FIGURE 10. Gradually increasing on-field rehabilitation exercises. Global coordination (A), skipping exercises (B and C), sport-specific exercises (D), and high-intensity exercises simulating playing situations (E).

gym and in the pool. The last phase of rehabilitation takes place on a specialized rehabilitation field under the supervision of rehabilitation specialists. On-field rehabilitation is designed as a sport-specific progression of exercises that allows gradual functional recovery of sport-specific skills, starting with in-line running and jumping and progressing to acceleration and deceleration drills, pivoting and cutting maneuvers at increasing speeds, and incorporation of sport-specific equipment and movement patterns.

On-field rehabilitation should consist of specific exercises and drills, lasting approximately 90 minutes, performed between 3 and 5 times a week (depending on the athlete's activity level) for at least 8 weeks. A significant aspect of on-field rehabilitation is dedicated to aerobic conditioning and sport-specific fitness exercises to facilitate the readiness for return to competition at the preinjury level and to reduce the risk of reinjury after successful return. Progression is always criteria-based, requiring the absence of pain and swelling and the maintenance of full ROM with the increasing activity demands. During this phase, the athlete should continue strengthening and flexibility exercises in the gym. A recent cohort study demonstrated that return to sport after arthroscopic ACI, accelerated by an on-field rehabilitation program, was achieved in 81% of cases with an average time of return of 10.6 months.[32]

On-field Rehabilitation Stages On-field rehabilitation is divided into 5 stages (**TABLE 5**), each characterized by well-defined, progressive, sport-specific exercises performed outdoors on a grass field or indoors on a synthetic field. Prior to the initiation of on-field rehabilitation, the patient performs an aerobic fitness test to identify aerobic and anaerobic thresholds used to personalize the intensity of each training session based on metabolic training loads. Aerobic and anaerobic thresholds are assessed by an incremental treadmill-running test, starting at 7 km/h, increasing by an increment of 2 km/h every 3 minutes until capillary blood lactate concentrations exceed 4 mmol/L.[31,152] Aerobic threshold is identified by a capillary blood lactate concentration of 2 mmol/L.[50] The heart rate that corresponds with the aerobic threshold is identified as the aerobic threshold training heart rate. Anaerobic threshold is identified by capillary blood lactate concentration of 4 mmol/L.[50] The heart rate that corresponds with the anaerobic threshold is identified as the anaerobic threshold training heart rate. During each training session, athletes wear a heart rate monitor to control the metabolic intensity of the training. Periodic reassessment of metabolic training load is performed to adjust the metabolic intensity to improve cardiorespiratory fitness for return to sport.

Stage 1. In the first few sessions, the patient walks along a straight line to gain confidence with the training environment, rehabilitation field, and the ground. Initially, a more compliant surface, such as sand, is used as an effective low-impact method for improving strength and proprioception. Once the athlete has become familiar with the training environment, slow running in a straight line is initiated, as well as global coordination exercises (agility drills) (**FIGURE 10A**). Throughout this phase, we recommend that athletes perform the exercises at or below their aerobic threshold. Athletes are progressed to the next phase, when they can perform these drills without pain, swelling, or apprehension.

Stage 2. At this stage, circular running and skipping exercises, advanced proprioception exercises, alternating running and stopping, and lateral slides/shuffles are introduced (**FIGURE 10B**). The patient also performs light jumps and soft landing on sand. Proper technique and optimal trunk and lower-limb alignment are emphasized through all exercises, with particular attention to the use of adequate hip and knee flexion and controlling for excessive knee abduction. Additionally, the metabolic requirements are increased, with athletes performing tasks between their aerobic and anaerobic thresholds. Aerobic conditioning is performed at the aerobic threshold for 10 to 15 minutes, and anaerobic conditioning is performed for less than 10% of the training time. To progress to the next phase, the athlete must demonstrate proper technique during all drills performed at near full speed, without pain, swelling, or apprehension.

Stage 3. The aerobic fitness test is repeated to establish new aerobic and anaerobic thresholds. Additionally, squat and countermovement jump tests are performed to measure jumping performance and lower extremity power. If available, the tests can be performed on a platform connected to a digital timer that records flight and contact time.[109] The athlete performs the squat jump by jumping from a semisquat position without countermovement, and the countermovement jump by allowing countermovement with the lower extremity prior to jumping. Markovic et al[109] found that these 2 tests were reliable and valid estimates of lower extremity power in physically active men. Accurate measurement of these 2 tasks can be useful to monitor progress over time.

This stage also includes progressive incorporation of changes in direction and speed, while running along with more intense agility drills and aerobic workouts (**FIGURE 10C**). Patients are allowed to begin practicing sport-specific skills without opponents. Aerobic conditioning is performed at the aerobic threshold for 15 to 20 minutes. Athletes can progress to the next phase when they demonstrate proper technique during all drills and during unopposed practice at near full speed, without pain, swelling, or apprehension.

Stage 4. Technical and sport-specific exercises are initiated, such as kicking or hitting a ball, changing direction and deceleration, and cutting and pivoting maneuvers with the ball or other sport-specific equipment (**FIGURE 10D**). Athletes also start incorporating rotational components to the jumping and landing drills. Aerobic threshold conditioning is performed for 15 to 20 minutes. Anaerobic threshold running is performed less than 50% of the training time. Athletes can progress to the next phase when they demonstrate proper technique during all drills performed at full speed, without pain, swelling, or apprehension.

Stage 5. During the last stage, the emphasis is on improving and intensifying sport-specific movement patterns, while simulating game-intensive conditions (**FIGURE 10E**). This can be done with controlled introduction of an opponent for one-on-one technical and agility drills. Aerobic conditioning is also conducted with more intense and prolonged aerobic workouts. Aerobic and anaerobic threshold tests and countermovement and squat jump tests are performed to help confirm progress and determine readiness to return to competition.

The progression of exercises during on-field rehabilitation follows the principles of strength training, conditioning, and increased functional demand with respect to the musculoskeletal and neuromuscular components involved in the recovery process.[43] Aerobic threshold conditioning is performed for 15 to 20 minutes. Anaerobic threshold running is performed greater than 50% of the training time. The criteria required for progression to athletic activity include completion of the sport-specific exercises and one-on-one opposed practice of sport-specific skills (1) without joint pain, swelling, or decreased ROM, (2) with proper coordination and neuromuscular control, and (3) without fear of reinjury.[32]

SUMMARY

Articular cartilage repair in athletes requires effective and durable joint surface restoration that can withstand the significant joint stresses generated during athletic activity. Several surgical techniques can successfully restore articular cartilage surfaces and allow for return to high-impact athletics after injury. Postoperative rehabilitation is a quintessential component of the treatment process for cartilage defects in the athlete. To optimize functional outcome and the ability to return to sport, cartilage repair rehabilitation in the athlete has to be adapted to the biology of the surgical repair technique, individual cartilage defect specifications, and each athlete's sport-specific demands. This can be achieved by a stepwise, phased rehabilitation approach using criteria-based progression of the athlete through the individual rehabilitation phases, based on a thorough understanding of the biomechanics and biology of cartilage injury and repair. Using these principles and close communication between surgical and rehabilitation teams, return to even demanding high-impact sport and continued sports participation can be successfully achieved. ◉

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