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Current Concepts in the Rehabilitation Following Articular Cartilage Repair Procedures in the Knee

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Postoperative rehabilitation programs following articular cartilage repair procedures will vary greatly among patients and need to be individualized based on the nature of the lesion, the unique characteristics of the patient, and the type and detail of each surgical procedure. These programs are based on knowledge of the basic science, anatomy, and biomechanics of articular cartilage as well as the biological course of healing following surgery. The goal is to restore full function in each patient as quickly as possible by facilitating a healing response without overloading the healing articular cartilage. The purpose of this paper is to overview the principles of rehabilitation following articular cartilage repair procedures. Furthermore, specific rehabilitation guidelines for debridement, abrasion chondroplasty, microfracture, osteochondral autograft transplantation, and autologous chondrocyte implantation will be presented based upon our current understanding of the biological healing response postoperatively. *J Orthop Sports Phys Ther 2006;36(10):774-794.* doi:10.2519/jospt.2006.2228

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Articular cartilage defects of the knee are a common cause of pain and functional disability in orthopedics and sports medicine. The avascular nature of articular cartilage predisposes the individual to progressive symptoms and degeneration due to the extremely slow and often times inability of the cartilage to heal.[6-10] Nonoperative rehabilitation and palliative care are frequently unsuccessful, and further treatment is required to alleviate symptoms. This presents a significant challenge for patients, particularly young and more active individuals, that present without gross degenerative changes but rather focal cartilage defects. Traditional methods of treatment, such as nonoperative treatment and lavage, have led to unfavorable results,[29,35,52] stimulating the need for newer surgical procedures designed to facilitate the repair or transplantation of autogenous cartilage tissue.

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Postoperative rehabilitation programs will vary greatly among patients and are individualized based on the characteristics of the lesion, patient, and surgery. Thus, the development of an appropriate rehabilitation program is challenging and must be highly individualized to assure successful outcomes. These programs are designed based upon knowledge of the basic science, anatomy, and biomechanics of articular cartilage, as well as the biological course of healing following surgery. The goal is to restore full function in each patient as quickly as possible without overloading the healing articular cartilage.

In this paper we will discuss the principles of rehabilitation following articular cartilage repair procedures, as well as specific rehabilitation guidelines for debridement, abrasion chondroplasty, microfracture, osteochondral autograft transplantation (OATS), and autologous chondrocyte implantation (ACI).

PRINCIPLES OF ARTICULAR CARTILAGE REHABILITATION

Several principles exist that must be considered when designing a rehabilitation program following articular cartilage repair proce-

dures. These key principles have been designed based on our understanding of the basic science and mechanics of articular cartilage. We will briefly describe each one below.

Individualization

An individualized approach for each patient is one of the most important principles involving the rehabilitation following articular cartilage repair procedures. There are several variables to consider when developing the unique rehabilitation progression for each patient. These include specifics regarding the patient, lesion, and surgery (Table 1).

The quality of each individual's articular cartilage is the result of several factors, including age, body mass index, general health, nutrition, and history of previous injuries. The composition of articular cartilage undergoes a gradual degeneration that results in a breakdown of tissue matrix and a reduction in the load-bearing capacity of the cartilage.[10] The specific factors that contribute to this deterioration remain controversial, but it appears that age, obesity, poor nutrition, joint malalignment (such as a varus knee), history of injury (such as ligamentous or meniscal injury), and a history of repetitive-impact loading (through work or sport activities) may result in osteoarthritic changes.[10] Thus, younger patients with isolated defects and relatively healthy surrounding articular cartilage oftentimes are able to progress their rehabilitation more rapidly than older individuals with more degenerative changes and less dense cartilage structure. Furthermore, the patient's motivation and previous activity levels must be considered when determining the rehabilitation approach to assure that the goals of each patient are addressed. The rehabilitation program should be individualized to the specific demands of each patient's activities of daily living, work, and/or sport activities.

There are also several variables to consider in regard to the lesion that may have a dramatic effect on the rehabilitation process. Most importantly is the exact location of the lesion. Rehabilitation of lesions on a weight-bearing surface of a femoral condyle must attempt to avoid deleterious compressive forces and require a different approach than for lesions located within the trochlea or retrosurface of the patella, where excessive shear forces should be minimized. The size, depth, and containment of each lesion must also be considered. Lesions that are large, deep, or poorly contained within healthy surrounding articular cartilage may require a slower rehabilitation progression than smaller, shallower, or well-contained lesions.

Lastly, the specifics of each surgical procedure will also influence the rehabilitation process. It is the authors' opinion that arthroscopic procedures, such as chondroplasty or microfracture, may progress at a different pace than procedures with larger incisions and greater tissue involvement, such as OATS or ACI, which require a slower rehabilitation process to protect the healing structures. Each specific surgical procedure also has different biological healing responses postoperatively.

TABLE 1. Variables that must be considered when designing postoperative rehabilitation protocols following articular cartilage procedures.

Lesion	Location
	Size
	Depth
	Containment
	Quality of surrounding tissue
Patient	Age
	Body mass index
	General health
	Nutrition
	Quality of articular cartilage
	Previous activity level
	Specific goals
	Motivation level
Surgery	Repair procedure
	Tissue involvement
	Concomitant procedures

Finally, any concomitant procedures to address alignment, stability, or meniscal function may also alter the rehabilitation program because of the need to protect other healing tissues.

Create a Healing Environment

The next principle of articular cartilage rehabilitation involves creating an environment that facilitates the healing process while avoiding potentially deleterious forces to the repair site. Through animal studies, as well as closely monitoring the maturation of repaired tissue in human patients via arthroscopic examination, the biological phases of maturation have been identified following several articular cartilage repair procedures.[4,5,20,42,43] Knowledge of the healing and maturation process following these procedures will assure that the repair tissue is gradually loaded and that excessive forces are not introduced too early in the healing process.

Two of the most important aspects of rehabilitation of articular cartilage procedures are weight-bearing restrictions and range-of-motion (ROM) limitations. Unloading and immobilization have been shown to be deleterious to healing articular cartilage, resulting in proteoglycan loss and gradual weakening.[2,21,59] Therefore, controlled weight bearing and ROM are essential to facilitate healing and prevent degeneration. This gradual progression has been shown to stimulate matrix production and improve the tissue's mechanical properties.[6,7,60]

FIGURE 1. Exercises such as a weight shift (Figure 1A) and leg press (Figure 1B) performed on a force platform (Balance Trainer; Unicam Corporation, Ramsey, NJ) that can measure the amount of weight distribution between each extremity.

Controlled compression and decompression forces observed during weight bearing may nourish the articular cartilage and provide the necessary signals to the repair tissue to produce a matrix that will match the environmental forces.[2,21,59] A progression of partial weight bearing with crutches is used to gradually increase the amount of load applied to the weight-bearing surfaces of the joint. The use of a pool or aquatic therapy may also be beneficial to initiate gait training and lower extremity weight-bearing exercises. The buoyancy of the water decreases the amount of weight-bearing forces to approximately 25% of the individual's body weight when submerged to the level of the axilla, and 50% of the individual's body weight when submerged to the level of the waist.[23] Commercially available devices to unload the patient's body weight during treadmill ambulation may also be useful.

A force platform is another useful tool during the early phases of rehabilitation when weight bearing is limited. This can be used to monitor the percentage of weight bearing on each extremity during exercises such as weight shifts, mini-squats, and leg presses (Figure 1).

The pool and force platforms may be used during early phases of rehabilitation to perform limited weight-bearing activities designed to facilitate a normal gait pattern and enhance strength, proprioception, and balance. The authors believe that beginning controlled weight-bearing activities during the early protective stage of healing is a critical component to the overall rehabilitation process. Although the return to functional activities will differ for each patient, it is our opinion that early initiation of controlled exercise enables the individual to return to functional activities sooner than those that are immobilized and non-weight bearing.

Passive range of motion (PROM) activities, such as continuous passive motion (CPM) machines or manual PROM performed by a rehabilitation specialist, are also performed immediately after surgery in a limited ROM to nourish the healing articular cartilage and prevent the formation of adhesions.[48-50,62] Motion exercises may assist in creating a smooth low frictional surface by sliding within the joint's articular surface, and may be an essential component to cartilage repair.[48,51] It is the authors' opinion that PROM is a safe and effective exercise to perform immediately postoperatively, with minimal disadvantageous shear or compressive forces, if performed with patient relaxation. This assures that muscular contraction does not create deleterious compressive pressures or shearing forces.

The use of CPM has been shown to enhance cartilage healing and long-term outcomes following articular cartilage procedures.[47,48] Comparing the outcomes of patients following microfracture procedures, Rodrigo et al[47] reported an 85% satisfactory outcome in patients utilizing a CPM machine for 6 to 8 hours per day for 8 weeks, as compared to 55% satisfactory outcome in those patients who did not utilize a CPM machine. PROM can also be performed on an isokinetic device (Biodex Corporation, Shirley, NY) in the passive mode or using a bike with adjustable pedals that can alter the available ROM (Unicam Corporation, Ramsey, NJ) (Figure 2).

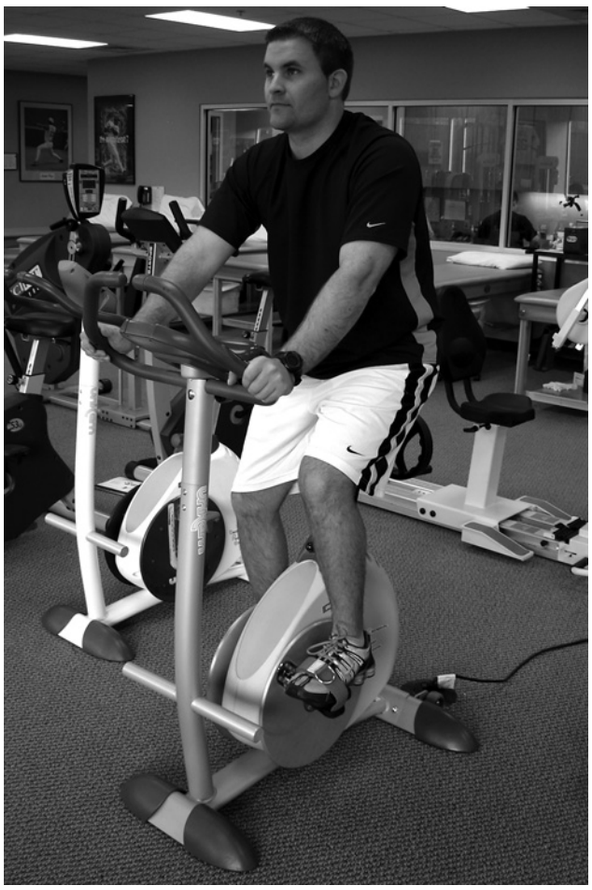

FIGURE 2. Bicycle riding on a Unicam machine (Unicam Corporation, Ramsey, NJ) that can adjust the pedal axis to alter the range of motion performed.

Biomechanics of the Knee

Knowledge of the biomechanics of the tibiofemoral and patellofemoral joints is essential to appropriately design rehabilitation programs following articular cartilage repair procedures to assure that exercises are selected and performed in a manner that does not cause deleterious forces to the repair site.

Articulation between the femoral condyle and tibial plateau is constant throughout knee ROM. Near-full knee extension the anterior surface of each femoral condyle is in articulation with the middle aspect of the tibial plateau. With weight bearing, as the knee moves into greater flexion, the femoral condyles progressively roll posteriorly and slide anteriorly, causing the articulation to shift posteriorly on the femoral condyles and tibial plateaus.[27,33]

The articulation between the inferior margin of the patella and the trochlea begins at approximately 10° to 20° of knee flexion depending on the size of the patella and the length of the patellar tendon.[26] With knee flexion, the contact area of the patellofemoral moves proximally. At 30°, the area of patellofemoral contact (inferior facets) is approximately 2.0 cm^2.[26] The area of contact gradually increases as the knee is flexed. At 60° of knee flexion, the middle facet of the patella articulates with the trochlea. At 90° of knee flexion, contact area increases up to 6.0 cm^2,[26] and the superior facets are in contact with the femoral condyles.

Using this knowledge of joint arthrokinematics, the rate of weight bearing, PROM, and exercise progression may be based on the exact location of the lesion (Figure 3).[3,14,15,19,34] For example, a patient with a lesion on the anterior aspect of the femoral condyle may perform exercises into deeper flexion without causing articulation at the repair site. Conversely, lesions on the posterior condyle may require the avoidance of exercise in deep knee flexion due to the rolling-and-sliding component of the articulation during deeper knee flexion. Furthermore, the rehabilitation program for lesions on the trochlea may include immediate partial weight bearing with a brace locked in full knee extension because the patella is not in contact with the trochlea in this position.

Rehabilitation exercises are also altered based on the biomechanics of the knee to avoid excessive compressive or shearing forces. While the exact ROM that articulation of the lesion occurs is the most important factor to consider when designing the rehabilitation program, the amount of compressive and shear forces observed at the joint also vary throughout the ROM. Exercises, such as seated knee extension, are commonly performed from 90° to 40° of knee flexion. This ROM provides the lowest amount of patellofemoral joint reaction forces while exhibiting the greatest amount of patellofemoral contact area.[25,26,58] Weight-bearing exercises, such as the leg press, vertical squats, lateral step-ups, and wall squats are performed initially from 0° to 30°, where tibiofemoral and patellofemoral joint reaction forces are lower.[25,26,58] Clinically, we begin these exercises using a leg press machine, rather than the vertical mini-squat, due to the better ability to control the amount of weight applied to the lower extremities. As the repair site heals and patient symptoms subside, the ROM in which exercises are performed is progressed to allow greater muscle strengthening over a greater range of movement. Exercises are progressed based on the patient's subjective reports of symptoms (pain, clicking, etc) and the clinical assessment of increased swelling and crepitation.

Reduction of Pain and Effusion

Patients often exhibit significant pain and effusion following articular cartilage repair procedures, specifically surgical procedures that require a large incision and soft tissue trauma, such as ACI and OATs. Numerous authors[24,40,56,61] have reported a progressive decrease in volitional quadriceps activity as the knee exhibits increased pain and distention. Therefore, the reduction in knee joint pain and swelling is

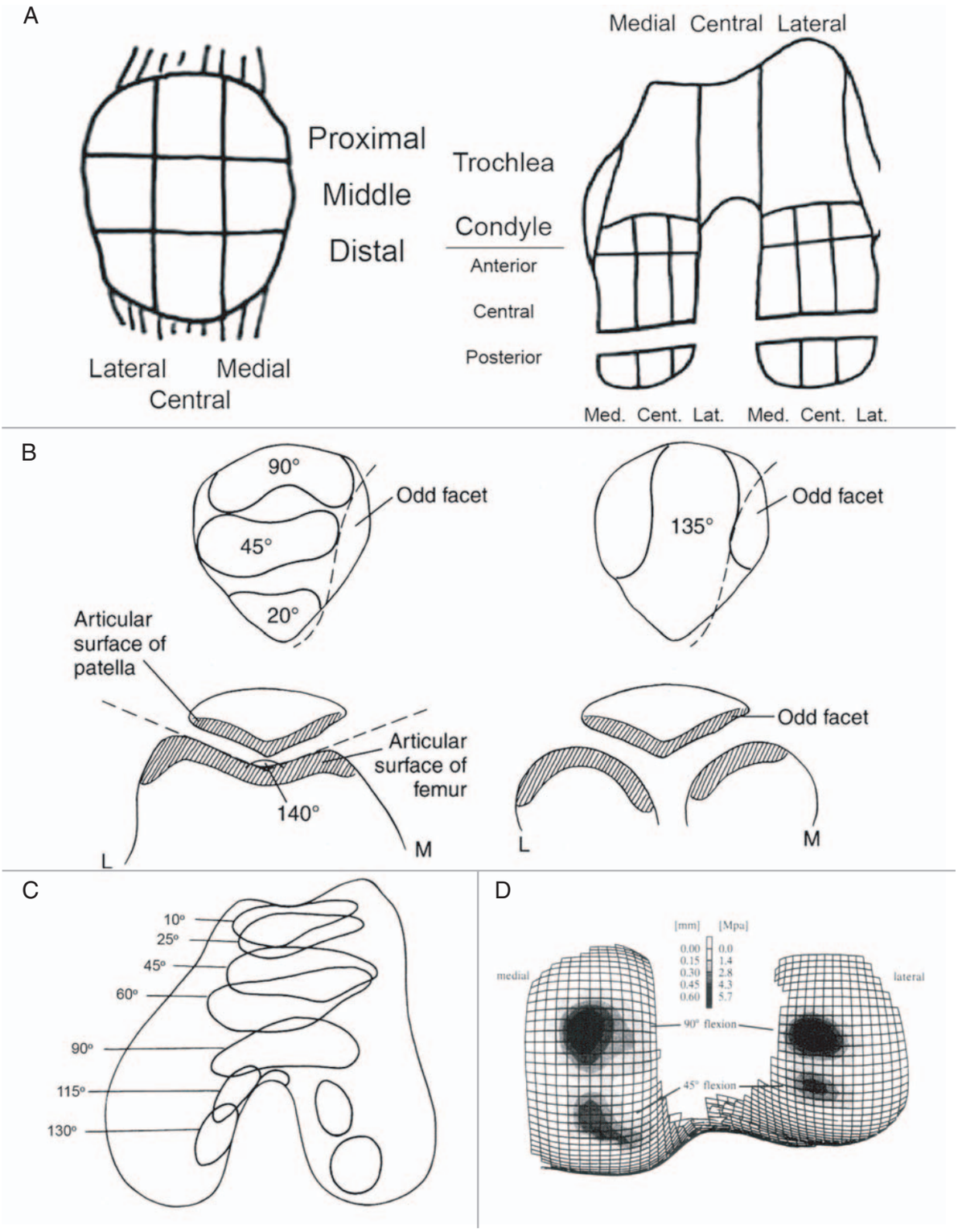

FIGURE 3. The lesion location diagram from the International Knee Documentation Committee can be used to document the location of articular cartilage lesions on the patella, trochlea, and femoral condyles (Figure 3A) (Reprinted with permission from the International Knee Documentation Committee). This form can be used in conjunction with knowledge of joint contact surfaces at various knee flexion angles for the patella (3B), trochlea (3C), and femoral condyles (3D) to help guide the selection of appropriate exercises. Reprinted with permission from McConnell J and Fulkerson J. The knee: patellofemoral and soft tissue injuries. In: Zachazewski JE, Magee DJ, Quillen WS, eds. *Athletic Injuries and Rehabilitation*. Philadelphia, PA: W.B. Saunders; 1996. And Blankevvort L, et al. Articular contact in a three-dimensional model of the knee. *J Biomechanics*. 1991;24(11):1019-1031.

FIGURE 4. Cryotherapy and intermittent compression applied through a commercial cold device (Gameready; Coolsystems Corporation, Berkeley, CA) with elevation and high-voltage electrical stimulation (300PV; Empi Corporation, St Paul, MN) for swelling control.

crucial to minimize this reflex inhibition and restore normal quadriceps activity. Furthermore, any increase in intra-articular joint temperature has been shown to stimulate proteoglytic enzyme activity, which has a detrimental effect on articular cartilage.[24,40]

Treatment options for swelling reduction include cryotherapy, elevation, high-voltage stimulation, and joint compression through the use of a knee sleeve or compression wrap (Figure 4). Patients presenting with chronic joint effusion may also benefit from a knee sleeve or compression wrap to apply constant pressure while performing everyday activities.

Pain can be reduced through the use of cryotherapy, transcutaneous electrical nerve stimulation, and analgesic medication. Immediately following injury or surgery, the use of a commercial cold wrap can be extremely beneficial. PROM may also provide neuromodulation of pain during acute or exacerbated conditions.[50]

Restore Soft Tissue Balance

One of the most important aspects of articular cartilage rehabilitation involves the avoidance of arthrofibrosis, particularly with the OATS and ACI procedures, due to the large open incision and extensive soft tissue trauma. This is achieved through the restoration of full passive knee extension, patellar mobility, and soft tissue flexibility of the knee and entire lower extremity. The inability to fully extend the knee results in abnormal joint arthrokinematics and subsequent increases in patellofemoral and tibiofemoral joint contact pressure, increased strain on the quadriceps muscle, and muscular fatigue.[41] Therefore, a drop-lock postoperative knee brace locked into 0° of extension is used during ambulation and PROM out of the brace is performed immediately following surgery.

The goal is to achieve at least 0° of knee extension within the first few days following surgery. Specific exercises to be performed include manual PROM exercises applied by the rehabilitation specialist, supine hamstring stretches with a wedge under the heel, and gastrocnemius stretching with a towel. Overpressure of 2.7 to 5.4 kg (6-12 lb) may be used for a low-load long-duration stretch as needed to achieve full extension. Modalities such as moist heat and ultrasound may also be applied to facilitate greater ROM improvements before and/or during these stretching techniques.[31,46]

The loss of patellar mobility following surgery may be due to various reasons, including excessive scar tissue adhesions from the incision anteriorly, as well as along the medial and lateral aspects of the knee. The loss of patellar mobility may result in ROM complications and difficulty recruiting quadriceps contraction. Patellar mobilizations in the medial-lateral and superior-inferior directions are performed by the rehabilitation specialist and independently by the patient during the home exercise program.

FIGURE 5. Neuromuscular electrical stimulation (300PV; Empi, Corporation, St Paul, MN) applied to the quadriceps muscle during exercises such as knee extension.

Soft tissue flexibility and pliability are also important for the entire lower extremity. Soft tissue mobilization and scar management is performed to prevent the development of adhesions around the anterior, medial, and lateral aspects of the knee. In addition, flexibility exercises are performed for the entire lower extremity, including the hamstrings, hip, and calf musculature. As ROM improves and the lesion begins to heal, quadriceps stretching may also be performed as tolerated by the patient.

Restoring Muscle Function

Due to the inhibition of the quadriceps muscle secondary to pain and effusion electrical muscle stimulation and biofeedback are often incorporated with therapeutic exercises to facilitate the active contraction of the quadriceps musculature in the acute stage of rehabilitation (Figure 5). The use of electrical stimulation and biofeedback appears to facilitate the return of muscle activation.[11,54] Clinically, we use electrical stimulation immediately following surgery while performing isometric and isotonic exercises such as quadriceps sets, straight leg raises, hip adduction and abduction, and knee extensions (Figure 5). Electrical stimulation is used when the patient presents acutely with the inability to activate the quadriceps in an attempt to recruit a maximum amount of muscle fibers during active contraction and may also be used throughout the rehabilitation process. Once independent muscle activation is present, biofeedback may be utilized to facilitate further neuromuscular activation of the quadriceps.

Exercises that strengthen the entire lower extremity, such as machine weights and weight-bearing exercises, may be included as the patient progresses to more advanced phases of rehabilitation. It is important not to concentrate solely on the quadriceps. Furthermore, the importance of incorporating core stability exercises cannot be overlooked. Training of the trunk, hip, and ankle musculature is emphasized to assist in controlling the production and dissipation of forces in the knee.

Enhance Proprioception and Neuromuscular Control

Proprioceptive and neuromuscular control drills of the lower extremities should be included to restore dynamic stabilization of the knee joint postoperatively. Proprioceptive deficits have been noted in the injured and postoperative knee.[12,45] Specific drills initially include weight shifting side-to-side, weight shifting diagonally, mini-squats, and mini-squats on an unstable surface such as a tilt or balance board (Figure 6). Perturbations can be added to challenge the neuromuscular system, as can additional exercises, including lunges, step-ups, and balance onto unstable surfaces (Figures 7 and 8).

FIGURE 6. Mini-squats on an unstable surface such as a tilt-board. The patient is instructed to squat while preventing movement of the board.

Controlling the Application of Loads

The next principle of rehabilitation involves gradually increasing the amount of stress applied to the injured knee as the patient returns to functional activities. This progression is used to provide a healthy stimulus for healing cartilage tissues, while assuring that forces are gradually applied without causing damage. Common clinical signs that a patient may be progressing too quickly and overloading the healing tissue are joint line pain and effusion. This should be monitored throughout the rehabilitation process.

Additionally, patients may benefit from the use of orthotics, insoles, and bracing to alter the applied loads on the articular cartilage during functional activities. These devices are used to avoid excessive forces by unloading the area of the knee where the lesion is located. Unloading braces are often used for patients with subtle uncorrected abnormal alignments

(such as genu varum), large or uncontained lesions, as well as in the presence of concomitant osteotomies and meniscal allografts (Figure 9).

Team Communication

Communication between the surgeon and therapist is essential to determine the accurate rate of progression based on the location of the lesion, size of the lesion, tissue quality of the patient, and the addition of concomitant surgical procedures. Also, communication between the medical team and patient is essential to provide the patient with education regarding the avoidance of deleterious forces, as well as improving the patient's compliance with precautions. Often times a preoperative physical therapy evaluation may be useful to mentally and physically prepare the patient for the articular cartilage procedure and postoperative rehabilitation.

REHABILITATION FOLLOWING ARTICULAR CARTILAGE REPAIR PROCEDURES

The rehabilitation progression is designed based on the 4 biological phases of cartilage maturation: proliferation, transitional, remodeling, and maturation.[4,5,13,20,22,39,42,43] The duration of each phase will vary depending on the lesion, patient, and the specifics of the surgery discussed previously; however, the concepts of each phase are consistent. The following is an overview of the general rehabilitation process during each of the 4 phases and may be applied to a variety of articular cartilage repair procedures.

FIGURE 7. Single leg balance on an unstable surface such as foam. The patient may use a weighted ball, while performing reciprocal movement patterns with the uninvolved upper and lower extremities to alter the patient's center of gravity throughout the exercise.

FIGURE 8. Lateral step-up exercises performed while standing on an unstable surface such as a piece of foam. This exercise requires eccentric control of the lower extremity to perform the step-up exercise as well as to balance throughout the movement.

Phase 1. Proliferation Phase

The first phase of cartilage healing requires protection of the repair and typically involves the first 4 to 6 weeks following surgery.[4,5,13,20,22,39,42,43] During this phase, the initial healing process begins and it is imperative to decrease swelling, gradually restore PROM and weight bearing, and enhance volitional control of the quadriceps.

Gradual PROM and controlled partial weight bearing will help to nurture the cartilage through diffusion of synovial fluid, as well as provide the proper stimulus for the cells to produce specific matrix markers.[2,6,7,21,59,60] Individuals begin with partial weight-bearing activities using crutches and progressive-loading exercises to gradually increase the amount of load applied to the weight-bearing surfaces of the joint. The use of a pool or aquatic therapy may be beneficial for gait training and lower extremity exercises once the incisions are well healed.

PROM exercises, performed by a rehabilitation specialist or CPM machines, are also performed immediately after surgery to nourish the healing articular cartilage and prevent the formation of adhesions.[47,48,62] The use of a CPM typically begins 6 to 8 hours following surgery and is performed for at least 2 to 3 weeks, with recommended use up to 6 to 8 weeks.[44,47] A CPM should be used throughout the day for a total time of 6 to 8 hours.[44,47] The patient is also instructed to perform active-assisted ROM frequently throughout the day. Patellar mobilization, soft tissue mobilization, and soft tissue flexibility exercises are also performed to minimize scar tissue formation and avoid loss of motion.

Early strengthening exercises are performed to restore volitional quadriceps control and neuromuscular control, through the use of concomitant electrical stimulation.[11,54] Exercises performed during this phase are limited based on the specific weight-bearing status of each patient. These typically include quadriceps sets, straight leg raises, and basic proprioception exercises such as weight shifting.

Phase 2. Transition Phase

This phase typically consists of weeks 4 through 12 postsurgery.[4,5,13,20,22,39,42,43] The repair tissue at this point is gaining strength, which will allow for the progression of rehabilitation exercises. During this phase the patient progresses from partial to full weight bearing while full ROM and soft tissue flexibility is achieved. Continued maturation of the repair tissue is fostered through higher level functional and motion exercises. It is during this phase that patients typically resume most normal activities of daily living. The rehabilitation program will gradually progress strengthening activities to include machine weights and weight-bearing exercises, such as leg press, front lunges, wall slides, and lateral step-ups, as the patient's weight-bearing status returns to normal.

The progression of weight-bearing activities and ROM restoration involves the gradual advancement of activities to facilitate healing and avoid postsurgical complications. Common complications include motion restrictions and scar tissue formation. Furthermore, an overaggressive approach early within the rehabilitation program may result in increased pain, inflammation, or effusion, as well as graft damage. Progression is controlled for strengthening exercises, proprioception training, neuromuscular control drills, and functional drills. For example, exercises such as weight shifts and lunges are progressed from straight-plane anterior-posterior or medial-lateral directions to involve multiplane and rotational movements. Exercises using 2 lower extremities, such as leg press and balance activities, are progressed to single lower extremity exercises. Thus the postoperative rehabilitation program involves a gradual progression of applied and functional stresses to provide a healthy stimulus for healing tissues without causing damage.

FIGURE 9. An osteoarthritis unloading brace (OA Defiance; DonJoy Corporation, Vista, CA) using a 4-point leverage system to unload the medial compartment of the knee by providing a mild valgus stress to the knee.

Phase 3. Remodeling Phase

This phase generally takes place from 3 to 6 months postoperatively.[4,5,13,20,22,39,42,43] During this phase there is a continuous remodeling of tissue into a more organized structure[4,5,13,20,22,39,42,43] that is increasing in strength and durability. As the tissue becomes firmer and integrated, it allows for more functional training activities to be performed. At this point, the patient typically notes improvement of symptoms and has normal ROM. The patient is

encouraged to continue with the rehabilitation program independently to maximize strength and flexibility. Low- to moderate-impact activities, such as bicycle riding, golfing, and recreational walking, may often be gradually incorporated.

Phase 4. Maturation Phase

The final phase begins in a range of 4 to 6 months and can last up to 15 to 18 months postsurgery.[4,5,13,20,22,39,42,43] It is during this phase that the repair tissue reaches its full maturation. The duration of this phase varies based on several factors such as lesion size and location, and the specific surgical procedure performed. The patient will gradually return to full premorbid activities as tolerated. Impact-loading activities are gradually introduced. Although such procedures as OATS and ACI are designed to restore function rather than return to high-impact athletic activities, a return to athletic activities is determined based on the unique presentation of each patient. A return to competitive athletics has been documented for microfracture,[57] OATS,[25] and ACI[37,38] procedures.

SPECIFIC POSTOPERATIVE GUIDELINES

Debridement and Chondroplasty

The rehabilitation following an arthroscopic debridement or chondroplasty is fairly simple due to the nature and goal of the procedure to facilitate tissue healing rather than to create repair tissue. The surgical procedure is performed arthroscopically and involves the use of a mechanical shaver or burr that is used to clean out the degenerative tissue and abrade the subchondral bone, thus facilitating the bone marrow elements to exude out onto the subchondral bone, allowing growth factors and undifferentiated cells to produce fibrocartilagenous tissue. This fibrocartilagenous tissue has been shown to deteriorate over time due to the inferior mechanical properties in comparison to normal hyaline articular cartilage.[8,9,28,36]

Initial weight bearing is limited for the first 3 to 5 days using axillary crutches, although weight bearing is permitted as tolerated. PROM exercises are progressed as tolerated immediately, with no postoperative limitations in motion. Full passive motion is typically achieved in 2 to 3 weeks. Non–weight-bearing exercises are performed initially, although weight-bearing strengthening exercises and bicycle riding are normally incorporated by the end of the first week. The patient is allowed to return to full functional activities and begin progressing to moderate-impact activities, such as light jogging and sports, beginning at week 4. The progression of impact loading may be delayed if significant degenerative changes are present within the knee or if symptoms of pain and/or effusion persist.

Microfracture

The microfracture procedure is a form of marrow stimulation, similar in concept to the chondroplasty procedure.[57] A sharp awl is used arthroscopically through 1 of the portals and a mallet is used to impact the awl into the subchondral bone and thus generate bleeding from the bone. This procedure is also referred to as ''picking,'' due to its nature. Holes are created at regular intervals until the entire defect has been addressed. The penetration of the subchondral bone eventually creates fibrocartilagenous tissue that covers the cartilage lesion.[57]

The rehabilitation following a microfracture procedure progresses more cautiously than that of a debridement or chondroplasty (Table 2). The proliferation phase begins immediately following surgery and lasts until the fourth week postoperatively. During this time, defects have been shown to begin filling with a fibrin clot, although no fibrocartilage is present.[13] A period of non-weight bearing is used for the first 2 to 4 weeks postoperatively for most lesions. A recent study by Marder et al[32] compared the results of patients with small focal lesions of less than 2.0 cm^2 utilizing 2 postoperative rehabilitation programs. Group 1 utilized touchdown weight bearing and a CPM machine for 6 to 8 hours a day for 6 weeks. Group 2 weight bearing as tolerated immediately following surgery with active-assisted heel slides for ROM (without the use of a CPM). The authors reported significant improvements in both groups and no significant differences in the subjective or objective outcomes of both groups with a minimum of 2 years follow-up. Thus, it appears that it may be possible to begin early controlled weight bearing for small, focal lesions without applying deleterious forces to the repair site.

We begin initial, controlled, toe touch weight bearing for lesions that are localized and smaller than 2.0 cm^2 in patients with good tissue quality. For patients with patellofemoral lesions, immediate weight bearing is performed due to the lack of lesion articular contact during weight bearing; however, a drop-locked knee brace is utilized to keep the knee in full extension and avoid deleterious shear forces to the healing repair site.

Due to the arthroscopic nature of the procedure, PROM is performed immediately without restrictions. Full PROM is achieved within weeks 3 to 4, often with little difficulty.

The transition phase begins at week 4 and lasts until week 8. It is during this time that the patient may progress to full weight bearing and more functional weight-bearing exercises. At 6 weeks postoperatively, a thin layer of tissue covers the base of the lesion.[17] Although the repair is still incomplete,

TABLE 2. Rehabilitation following microfracture procedure.

Phase 1. Proliferation phase (weeks 0-4)

Goals
- Protect healing tissue from load and shear forces
- Decrease pain and effusion
- Restoration of full passive knee extension
- Gradually restore knee flexion
- Regain quadriceps control

Brace
- No brace, may use elastic wrap to control swelling

Weight-bearing (WB)
- WB status varies based on lesion location and size
- For medium to large femoral condyle lesions (>2.0 cm^2): non-weight bearing for 2 wk; begin toe touch WB (approximately 9.1-13.6 kg) at week 3; progress to partial WB (approximately 1/4 body weight) at week 4
- For small femoral condyle lesions (<2.0 cm^2): immediate toe-touch WB (per physician) (approximately 9.1-13.6 kg) at weeks 0-2; progress to 50% WB by week 3; 75% WB by week 4
- For patellofemoral lesions: immediate toe-touch WB of approximately 25% body weight with brace locked in full extension; progress to 50% WB at week 2 and 75% WB week 3 with brace locked in full extension, full WB week 4

Range of motion (ROM)
- Immediate motion exercise day 1
- Full passive knee extension immediately
- Initiate CPM day 1 for total of 8-12 h/d (0°-60°; if patellofemoral lesion >6.0 cm^2, 0°-40°)
- Progress CPM ROM as tolerated 5°-10° per day
- May continue CPM for total of 6-8 hours per day for up to 6 weeks
- Patellar mobilization (4-6 times per day)
- Motion exercises throughout the day
- Passive knee flexion ROM at least 2-3 times daily
- Progress passive knee ROM as tolerated, no restrictions
- Minimum ROM goals: 0°-90° week 1, 0°-105° week 2, 0°-115° week 3, and 0°-125° week 4
- Stretch hamstrings and calf

Strengthening program
- Ankle pump using elastic tubing
- Quadriceps setting
- Multi-angle isometrics (cocontractions Q/H)
- Active knee extension 90°-40° for femoral condyle lesions (no resistance), avoid for patellofemoral lesions
- Straight leg raises (4 directions)
- Electrical muscle stimulation and/or biofeedback during quadriceps exercises
- Initiate weight shifting exercises with knee in extension week 1-2 for patellofemoral lesions and small femoral condyle lesions, week 3 for larger femoral condyle lesions
- Leg press 0°-60° week 3 for small femoral condyle lesions and patellofemoral lesions, progress to 0°-90° week 4
- Toe calf raises week 4 for small femoral condyle and patellofemoral lesions
- May begin use of pool for gait training and exercises week 3-4 (when incision is fully healed)
- May begin stationary bike week 3-4, low resistance
- No active knee extension exercises for patellofemoral lesions

Functional activities
- Gradual return to daily activities
- If symptoms occur, reduce activities to reduce pain and inflammation

Swelling control
- Ice, elevation, compression, and modalities as needed

Criteria to progress to phase 2
- Full passive knee extension
- Knee flexion to 125°
- Minimal pain and swelling
- Voluntary quadriceps activity

Phase 2. Transition phase (weeks 4-8)

Goals
- Gradually improve quadriceps strength/endurance
- Gradual increase in functional activities

WB
- Progress WB as tolerated
- For large femoral condyle lesions: 1/2 body weight with crutches at 6 weeks; 75% WB week 7; progress to full WB at 8 weeks, discontinue crutches

ROM
- Gradual increase in ROM
- Maintain full passive knee extension

TABLE 2 (continued)

- Progress knee flexion to 135°+ by week 8
- Continue patellar mobilization and soft tissue mobilization as needed
- Continue stretching program

Strengthening exercises

- Progress WB exercises
- Initiate leg press for large femoral condyle lesions week 6
- Mini-squats 0°-45° week 7
- Toe-calf raises week 8 for femoral condyle lesions
- Progress balance and proprioception drills
- Initiate front lunges, wall squats, front and lateral step-ups week 5 for small femoral condyle and patellofemoral lesions, week 8 for large femoral condyle lesions
- For femoral condyle lesions, progress non-WB knee extension, 0.45 kg/wk
- For patellofemoral lesion, may begin non-WB knee extension without resistance in a ROM that does not allow for articulation of the lesion
- Continue stationary bicycle, low resistance (gradually increase time)
- Continue use of electrical muscle stimulation and or biofeedback as needed
- Continue use of pool for gait training and exercise

Functional activities

- As pain and swelling diminish, the patient may gradually increase functional activities
- Gradually increase standing and walking

Criteria to progress to phase 3

- Full ROM
- Acceptable strength level
- Hamstrings within 20% of contralateral extremity
- Quadriceps within 30% of contralateral extremity
- Balance testing within 30% of contralateral extremity
- Able to bike for 30 min

Phase 3. Remodeling phase (weeks 8-16)

Goals

- Improve muscular strength and endurance
- Increase functional activities

ROM

- Patient should exhibit 125°-135°+ flexion

Exercise program

- Leg press (0°-90°)
- Bilateral squats (0°-60°)
- Unilateral step-ups progressing from 5.1 to 20.3 cm
- Forward lunges
- Walking program week 10
- Progress non-WB extension (0°-90°); for patellofemoral lesions, may begin week 12, perform from 90°-40° or avoid angle where lesion articulates; progress 0.45 kg every 2 weeks, beginning week 20 if no pain or crepitation, must monitor symptoms
- Continue progressing balance and proprioception
- Bicycle
- Stairmaster
- Swimming
- Nordic-Trak/elliptical

Functional activities

- Increase walking (distance, cadence, incline, etc)

Maintenance program

- Initiate at weeks 12-16
- Bicycle: low resistance, increase time
- Progressive walking program
- Pool exercises for entire lower extremity
- Straight leg raises
- Leg press
- Wall squats
- Hip strengthening (abduction/adduction)
- Front lunges
- Step-ups
- Stretch quadriceps, hamstrings, calf

Criteria to progress to phase 4

- Full nonpainful ROM
- Strength within 80%-90% of contralateral extremity
- Balance and/or stability within 75%-80% of contralateral extremity
- No pain, inflammation, or swelling

TABLE 2 (continued)

Phase 4. Maturation phase (weeks 16-26)
Goals
• Gradual return to full unrestricted functional activities
Exercises
• Continue maintenance program progression 3-4 times per wk
• Progress resistance as tolerated
• Emphasis on entire lower extremity strength and flexibility
• Progress agility and balance drills
• Impact loading program should be individualized to the patient's needs
• Progress sport programs depending on patient variables
Functional activities
• Patient may return to various sport activities as progression in rehabilitation and cartilage healing allows. Generally, low-impact sports, such as swimming, skating, rollerblading, and cycling, are permitted at about 2 months for small femoral condyle and patellofemoral lesions and at 3 months for large femoral condyle lesions. Higher-impact sports such as jogging, running, and aerobics may be performed at 4 months for small lesions or 5 months for larger lesions. High-impact sports, such as tennis, basketball, football and baseball, are allowed at 6-8 mo

Abbreviations: CPM, continuous passive motion; Q/H, quadriceps/hamstring.

fibrocartilagenous tissue is present and by 8 weeks some tissue with hyaline-like characteristics has been detected.[13] By 12 weeks the defect is completely filled and the quality of cartilaginous tissue improves significantly.[17]

Weight bearing is thus progressed to full at week 8 for most lesions, when the strength of the repair tissue is increasing. However, the progression to more advanced exercises including impact loading is delayed until the end of the remodeling phase, when the defect is completely filled. The patient may gradually begin to return to former activities during the maturation phase between months 4 to 6; however, larger lesions require delaying the progression to high-impact activities for up to 8 months.

OATs

While marrow stimulation techniques (chondroplasty and microfracture) often have initial success in symptom reduction and the restoration of function, several studies have shown a gradual deterioration of the fibrocartilagenous tissue over time.[8,9,28,36] Other procedures have been designed to attempt to repair cartilage defects with type II hyaline articular cartilage similar to that of the native cartilage. Theoretically, this type of repair should resemble the normal biomechanical strength of the original cartilage and thus be more resilient to deterioration.[4,5,22,42,43] The OATs procedure involves the transplantation of plugs of bone with overlying articular cartilage that are harvested from non–weight-bearing areas of the knee (such as the proximal lateral trochlea or the intercondylar notch area).[1] These plugs are round and range in size to match the size and shape of the defect. The harvested plugs are then implanted into holes drilled to receive the specifically sized grafts within the defect. Several plugs of similar or varying size can be utilized to fill the defect as much as possible, which is why this procedure is also referred to as mosaicplasty. Due to the extent of the procedure, this surgery is done through an open incision.

Rehabilitation following OATs procedures requires the avoidance of early deleterious forces to avoid disrupting the healing transplanted bone plugs Table 3. Currently we alter the pace of the rehabilitation program following OATS procedures based not only on the size of the lesion, but also the amount of transplanted bone plugs. We progress more cautiously when numerous bone plugs are used due to the potential for a less congruent surface. The early proliferation phase lasts until the eighth week postoperatively. A 44% reduction in the push-in and pull-out strength of the transplanted bone plugs has been observed at 1 week postoperatively,[61] emphasizing the need for strict non-weight bearing early after surgery. We typically begin partial weight bearing 2 to 4 weeks following surgery, based on the size of the lesion and the number of transplanted bone plugs utilized. Although the original hyaline cartilage remains intact and viable,[39] the strength of the bone plugs is the limiting factor when designing the postoperative rehabilitation program.

By 4 weeks, the cancellous bone plugs are united[22] and by 6 weeks there is full subchondral integration and 29% of grafts have shown bonding between the articular cartilage of the bone plugs and the surrounding articular cartilage.[39] Although integration has occurred, a 63% decrease in graft stiffness is still observed at 6 weeks postoperative.[39] During this time, weight bearing is gradually progressed as the strength of the repair increases. At 8 weeks postoperative, fibrocartilage has been observed to grow to the surface and seal the recipient and donor site hyaline cartilage, and progression is made to full weight bearing. Immediate weight bearing is initiated for patellofemoral lesions with the patient using a drop-lock knee brace and progressed to full weight bearing

TABLE 3. Rehabilitation following osteochondral autograft transplantation.

Phase 1. Proliferation phase (weeks 0-6)

Goals
- Protection of healing tissue from load and shear forces
- Decrease pain and effusion
- Restoration of full passive knee extension
- Gradual improvement of knee flexion
- Regaining quadriceps control

Brace
- Locked at 0° during weight-bearing (WB) activities
- Sleep in locked brace for 2-4 wk

WB
- WB status varies based on lesion location and size
  - For femoral condyle lesions: non-WB for 2-4 wk (physician direction); if large lesion (>5cm^2) may need to delay WB up to 4 wk, progress to toe touch WB (approximately 9.1-13.6 kg) at weeks 3-4 and partial WB (approximately 25%-50% body weight) at week 6
  - For patellofemoral lesions: immediate toe-touch WB at 25% body weight with brace locked in full extension. Progress to 50% WB week 2-3 in brace and 75% WB week 4-5 in brace

Range of motion (ROM)
- Immediate motion exercise day 1
- Full passive knee extension immediately
- Initiate CPM day 1 for total of 8-12 h/d (0°-60°; if patellofemoral lesion >6.0 cm^2, 0°-40°)
- Progress CPM ROM as tolerated 5°-10° per day
- May continue CPM for total of 6-8 h/d for up to 6 wk
- Patellar mobilization (4-6 times per day)
- Motion exercises throughout the day
- Passive knee flexion ROM at least 2-3 times daily
- Passive knee ROM as tolerated
- For femoral condyle lesions, minimum knee flexion ROM goal is 90° by 1-2 wk, 105° by week 3, 115° by week 4, and 120°-125° by week 6
- For patellofemoral lesions, minimum knee flexion ROM goal is 90° by weeks 2-3, 105° by weeks 3-4, and 120° by week 6
- Stretch hamstrings and calf

Strengthening program
- Ankle pump using elastic tubing
- Quadriceps setting
- Multi-angle isometrics (cocontractions Q/H)
- Straight leg raises (4 directions)
- Active knee extension 90°-40° for femoral condyle lesions, if no articulation of lesion in this ROM, week 4 (no resistance)
- Electrical muscle stimulation and/or biofeedback during quadriceps exercises
- Stationary bicycle when ROM allows, low resistance
- Isometric leg press at week 4 (multi-angle)
- May begin use of pool for gait training and exercises week 6
- Initiate weight shifting exercises with knee in extension weeks 3-4 for patellofemoral lesions
- No active knee extension exercises for patellofemoral lesions
- No weight-bearing exercises for femoral condyle lesions

Functional activities
- Gradual return to daily activities
- If symptoms occur, reduce activities to reduce pain and inflammation
  - Extended standing should be avoided

Swelling control
- Ice, elevation, compression, and modalities as needed to decrease swelling

Criteria to progress to phase 2
- Full passive knee extension
- Knee flexion to 120°
- Minimal pain and swelling

Phase 2. Transition phase (weeks 6-12)

Goals
- Gradually increase to full ROM and WB
- Gradually improve quadriceps strength/endurance
- Gradual increase in functional activities

Brace
- Discontinue brace at 6 wk, consider unloading brace for femoral condyle lesions

WB
- Progress WB as tolerated
  - For femoral condyle lesions: 75% body weight with crutches at 6-7 wk, and progress to full WB at 8-10 wk, may need to delay full WB up to 14 wk if large lesion, discontinue crutches at 8-10 wk
  - For patellofemoral lesions progress to full WB and discharge crutches at 6-8 wk

TABLE 3 (continued)

ROM
- Gradual increase in ROM
- Maintain full passive knee extension
- Progress knee flexion to 125°-135° by weeks 8-10
- Continue patellar mobilization and soft tissue mobilization, as needed
- Continue stretching program

Strengthening exercises
- Initiate weight shifts weeks 6-8 for femoral condyle lesions
- Initiate mini-squats 0°-45° by weeks 6-8 for patellofemoral lesions
- WB exercises (leg press) weeks 8-10 for femoral condyle lesions: mini-squats 0°-45°, front lunges, step-ups, wall squats; may need to delay WB exercises up to 14 wk if large lesions
- Leg press weeks 8-10 (0°-90° for femoral condyle; 0°-60° for patellofemoral, progressing to 0°-90° as tolerated)
- Toe-calf raises weeks 10-12
- Progress active knee extension: begin resistance from 0°-90° with femoral condyle lesions progressing 0.45 kg every 10-14 d; for patellofemoral lesions begin with 0°-30° (minimal articulation) at week 12 and progress to deeper angles as tolerated
- Stationary bicycle (gradually increase time)
- Balance and proprioception drills
- Continue use of electrical stimulation and biofeedback as needed
- Continue use of pool for gait training and exercise

Functional activities
- As pain and swelling diminish, the patient may gradually increase functional activities
- Gradually increase standing and walking

Criteria to progress to phase 3
- Full ROM
- Acceptable strength level
  - Hamstrings within 20% of contralateral extremity
  - Quadriceps within 30% of contralateral extremity
- Balance testing within 30% of contralateral extremity
- Able to bike for 30 min

Phase 3. Remodeling phase (weeks 12-26)

Goals
- Improve muscular strength and endurance
- Increase functional activities

ROM
- Patient should exhibit 125°-135° flexion, no restrictions

Exercise program
- Continue progressing exercises
- Leg press 0°-90°
- Bilateral squats (0°-60°)
- Unilateral step-ups progressing from 5.1 to 20.3 cm
- Forward lunges
- Begin walking program on treadmill
- Non-WB knee extension (0°-90°) as tolerated, do not progress to heavy resistance with patellofemoral lesions, must monitor symptoms of pain and crepitation
- Bicycle
- Stairmaster
- Swimming
- Nordic-Trak/elliptical

Functional activities
- Increase walking (distance, cadence, incline, etc)

Maintenance program
- Initiate at weeks 16-20
  - Bicycle, low resistance
  - Progressive walking program
  - Pool exercises for entire lower extremity
  - Straight leg raises into flexion
  - Leg press
  - Wall squats
  - Hip strengthening (abduction/adduction)
  - Front lunges
  - Stretch quadriceps, hamstrings, gastrocnemius

Criteria to progress to phase 4
- Full nonpainful ROM
- Strength within 80%-90% of contralateral extremity

TABLE 3 (continued)

- Balance and/or stability within 75%-80% of contralateral extremity
- No pain, inflammation, or swelling

Phase 4. Maturation phase (weeks 26-52)

Goals
- Gradual return to full unrestricted functional activities

Exercises
- Continue maintenance program progression 3-4 times per wk
- Progress resistance as tolerated
- Emphasis on entire lower extremity strength and flexibility
- Progress agility and balance drills
- Impact loading program should be individualized to the patient's needs
- Progress sport programs depending on patient variables

Functional activities
- Patient may return to various sport activities as progression in rehabilitation and cartilage healing allows. Generally, low-impact sports, such as skating, rollerblading, and cycling, are permitted at about 6-8 mo. Higher-impact sports such as jogging, running, and aerobics may be performed at 8-10 mo. High-impact sports such as tennis, basketball, and baseball, are allowed at 12-18 mo

Abbreviations: CPM, continuous passive motion; Q/H, quadriceps/hamstring.

without the brace at approximately 6 to 8 weeks postoperatively.

ROM during the early protective phase is gradually progressed to assure that adhesion formation and loss of motion is avoided. Due to the large incision and invasive nature of the procedure, motion is progressed gradually to assure that effusion formation is minimized.

Exercises are progressed from non–weight-bearing exercises, such as quadriceps sets and multi-angle straight leg raises, to gentle weight-bearing exercises after week 6.

During the transition phase, full ROM and weight bearing are achieved, typically between weeks 8 and 10, although patients with larger lesions may need to further delay the progression to full weight bearing for up to 12 to 14 weeks. At this point the strengthening program is progress to include weight bearing and machine exercises. Again, it is during this phase that patients return to low-impact functional activities.

During the remodeling and maturation phases, strength, proprioception, and neuromuscular control are enhanced while gradually applying impact-loading stresses as tolerated without an increase in symptoms. Patients may return to various sport activities as the progression in rehabilitation and cartilage healing allows. Generally, low-impact sports such as skating, rollerblading, and cycling are permitted at about 6 to 8 months. Higher-impact sports, such as jogging, running, and aerobics, may be performed at 8 to 10 months. High-impact sports, such as tennis, basketball, and baseball, are allowed at 12 to 18 months.

ACI

Another procedure designed to generate hyaline cartilage is ACI. Rather than using large transplanted bone plugs from within the patient's own knee, this procedure involves biotechnology to facilitate the growth of chondrocytes in a laboratory from a small piece of cartilage harvested from the patient's own knee.[18] The harvest of the cartilage is carried out arthroscopically. Several weeks are necessary for the cells to be adequately isolated and multiplied. The implantation of chondrocytes is accomplished via a second surgery that requires an open arthrotomy of the knee. During this second surgery, a patch of periosteum, sized to cover the defect, is harvested from the medial border of the midshaft of the tibia. The periosteum is sewn over the defect using sutures. Once in place, a fibrin glue is used to seal the edges of the patch to create a watertight seal and the chondrocytes are injected beneath the patch. The injected chondrocytes gradually mature and form tissue that is mostly composed of type II hyaline-like cartilage.[42,43]

The rehabilitation program following chondrocyte implantation is vital for success and long-term outcomes of the procedure (Table 4). Early, controlled ROM and weight bearing are necessary to stimulate chondrocyte development; although caution is placed on overaggressive activities that may result in cell damage or graft delamination.

Rehabilitation may begin as early as 4 hours postoperatively in the form of CPM. At this time, the chondrocytes are aligned and attach to the underlying surface of the defect.[55] It is imperative that the patient be appropriately positioned to allow for the effect of gravity to evenly distribute the chondrocytes on the base of the defect during these first 4 hours as the cells adhere to the surface. A recent study by Sohn et al[55] has shown that the defect orientation during these first 4 hours can be an important factor in the uniformity of cell distribution. For example, patients with patellofemoral lesions are positioned in the prone position for the first 4 hours postoperatively to ensure that the chondrocyte distribution is

TABLE 4. Rehabilitation following autologous chondrocyte implantation.

Phase 1. Proliferation phase (weeks 0-6)

Goals
- Protect healing tissue from load and shear forces
- Decrease pain and effusion
- Restoration of full passive knee extension
- Gradually improve knee flexion
- Regain quadriceps control

Brace
- Locked at 0° during weight-bearing (WB) activities
- Sleep in locked brace for 2-4 wk

WB
- WB status varies based on lesion location and size
- For femoral condyle lesions
  - Non-WB for 1-2 wk, may begin toe touch WB immediately per physician if lesion <2.0 cm^2; begin toe touch weight bearing (approximately 9.1-13.6 kg) weeks 2-3; progress to partial WB (approximately ¼ body weight) at weeks 4-5
  - For patellofemoral lesions: immediate toe-touch WB of ~25% body weight with brace locked in full extension; progress to 50% WB at week 2 and 75% WB weeks 3-4 with brace locked in full extension

Range of motion (ROM)
- Immediate motion exercise day 1
- Full passive knee extension immediately
- Initiate CPM day 1 for total of 8-12 h/d (0°-60°; if patellofemoral lesion >6.0 cm^2, 0°-40°)
- Progress CPM ROM as tolerated 5°-10°/d
- May continue CPM for total of 6-8 h/d for up to 6 wk
- Patellar mobilization (4-6 times per d)
- Motion exercises throughout the day
- Passive knee flexion ROM at least 2-3 times daily
- Passive knee ROM as tolerated
- For femoral condyle lesions, knee flexion ROM goal is 90° by weeks 1-2, 105° by week 3, 115° by week 4, and 120°-125° by week 6
- For patellofemoral lesions, knee flexion ROM goal is 90° by weeks 2-3, 105° by 3-4 weeks, and 120° by week 6
- Stretch hamstrings and calf

Strengthening program
- Ankle pump using elastic tubing
- Quadriceps setting
- Multi-angle isometrics (cocontractions Q/H)
- Active knee extension 90°-40° for femoral condyle lesions (no resistance)
- Straight leg raises (4 directions)
- Stationary bicycle when ROM allows, low resistance
- Electrical muscle stimulation and/or biofeedback during quadriceps exercises
- Isometric leg press at week 4 (multi-angle)
- May begin use of pool for gait training and exercises week 4
- Initiate weight-shifting exercises with knee in extension by weeks 2-3 for patellofemoral lesions
- No active knee extension exercises for patellofemoral lesions

Functional activities
- Gradual return to daily activities
- If symptoms occur, reduce activities to reduce pain and inflammation
- Extended standing should be avoided

Swelling control
- Ice, elevation, compression, and modalities as needed to decrease swelling

Criteria to progress to phase 2
- Full passive knee extension
- Knee flexion to 120°
- Minimal pain and swelling
- Voluntary quadriceps activity

Phase 2. Transition phase (weeks 6-12)

Goals
- Gradually increase ROM
- Gradually improve quadriceps strength/endurance
- Gradual increase in functional activities

Brace
- Discontinue brace at week 6
- Consider unloading knee brace for femoral condyle lesions

TABLE 4 (continued)

WB
- Progress WB as tolerated
  - For femoral condyle lesions: ½ body weight with crutches at 6 wk, progress to full WB at 8-9 wk, discontinue crutches
  - For patellofemoral lesions: progress to full WB at 6-8 wk, discontinue crutches

ROM
- Gradual increase in ROM
- Maintain full passive knee extension
- Progress knee flexion to 125°-135° by week 8
- Continue patellar mobilization and soft tissue mobilization, as needed
- Continue stretching program

Strengthening exercises
- Progress WB exercises
- Initiate weight shifts week 6 for femoral condyle lesions
- Leg press weeks 7-8
- Mini-squats 0°-45° by week 8
- Toe-calf raises at week 6 for patellofemoral lesions, at week 8 for femoral condyle lesions
- Progress balance and proprioception drills
- Initiate front lunges, wall squats, front and lateral step-ups by weeks 8-10
- For femoral condyle lesions, progress non-WB knee extension, 0.45 kg/wk
- For patellofemoral lesion, may begin non-WB knee extension without resistance in a ROM that does not allow for articulation of the lesion
- Stationary bicycle, low resistance (gradually increase time)
- Treadmill walking program by weeks 10-12
- Continue use of electrical muscle stimulation and or biofeedback as needed
- Continue use of pool for gait training and exercise

Functional activities
- As pain and swelling diminish, the patient may gradually increase functional activities
- Gradually increase standing and walking

Criteria to progress to phase 3
- Full ROM
- Acceptable strength level
- Hamstrings within 20% of contralateral extremity
- Quadriceps within 30% of contralateral extremity
- Balance testing within 30% of contralateral extremity
- Able to walk 1.6-3.2 km or bike for 30 min

Phase 3. Remodeling phase (weeks 12-26)

Goals
- Improve muscular strength and endurance
- Increase functional activities

ROM
- Patient should exhibit 125°-135° flexion

Exercise program
- Leg press (0°-90°)
- Bilateral squats (0°-60°)
- Unilateral step-ups progressing from 5.1 to 20.3 cm
- Forward lunges
- Walking program
- Progress non-WB extension (0°-90°), for patellofemoral lesions perform from 90°-40° or avoid angle where lesion articulates, progress 0.45 kg every 2 wk beginning week 20 if no pain or crepitation, must monitor symptoms
- Continue progressing balance and proprioception
- Bicycle
- Stairmaster
- Swimming
- Nordic-Trak/elliptical

Functional activities
- Increase walking (distance, cadence, incline, etc)

Maintenance program
- Initiate at weeks 16-20
- Bicycle: low resistance, increase time
- Progressive walking program
- Pool exercises for entire lower extremity
- Straight leg raises
- Leg press
- Wall squats
- Hip abduction/adduction

TABLE 4 (continued)

- Front lunges
- Step-ups
- Stretch quadriceps, hamstrings, calf

Criteria to progress to phase 4

- Full nonpainful ROM
- Strength within 80%-90% of contralateral extremity
- Balance and/or stability within 75%-80% of contralateral extremity
- No pain, inflammation, or swelling

Phase 4. Maturation phase (weeks 26-52)

Goals

- Gradual return to full unrestricted functional activities

Exercises

- Continue maintenance program progression 3-4 times per wk
- Progress resistance as tolerated
- Emphasis on entire lower extremity strength and flexibility
- Progress agility and balance drills
- Impact loading program should be individualized to the patient's needs
- Progress sport programs depending on patient variables

Functional activities

- Patient may return to various sport activities as progression in rehabilitation and cartilage healing allows. Generally, low-impact sports, such as swimming, skating, rollerblading, and cycling, are permitted at about 6 mo. Higher-impact sports, such as jogging, running, and aerobics, may be performed at 8-9 mo for small lesions or 9-12 mo for larger lesions. High-impact sports, such as tennis, basketball, football, and baseball, are allowed at 12-18 mo

Abbreviations: CPM, continuous passive motion; Q/H, quadriceps/hamstring.

aligned on the base of the lesion rather than along the periosteal patch, if positioned in the traditional supine position.

Proliferation of the chondrocytes occurs in the first 6 weeks following cell implantation. During the first 24 hours after cell implantation, the cells line the base of the lesion and multiply several times to produce a matrix that will fill the defect with a soft repair tissue up to the level of the periosteal cover.[20,43] At this time, PROM and controlled partial weight bearing will help to promote cellular nutrition through synovial fluid diffusion as well as provide the proper stimulus for the cells to produce specific matrix markers. During this initial phase, controlled PROM and a gradual weight-bearing progression are 2 of the most important components to the rehabilitation process.

Immediate toe-touch weight bearing is performed on smaller lesions, progressing to 25% body weight at weeks 2 to 4, 50% body weight at weeks 5 to 6, and finally full weight bearing at week 8. This progression may be delayed approximately 2 weeks, with 2 weeks of non-weight bearing, if the lesion is large, deep, or uncontained. For lesions within the patella or trochlea, the patient is allowed to weight bear as tolerated immediately after surgery with a brace locked in full extension. ROM is progressed cautiously to avoid swelling, with a goal of 90° of flexion at week 1, 105° at weeks 2 and 3, 115° at week 4, and 125° at week 6. Early strength and proprioceptive exercises are performed within the patient's weight-bearing status.

During the transition phase, which includes weeks 7 through 12, the repair tissue at this point is spongy and compressible with little resistance. Upon arthroscopic examination the tissue may in fact have a wave-like motion to it when sliding a probe over its surface.[20,43] During this phase the patient achieves full ROM and progresses from partial weight bearing to full weight bearing. Continued maturation of the repair tissue is fostered through higher-level functional and motion exercises. Weight-bearing exercises, such as front lunges, step-ups, and wall squats, are performed as well as machine exercises for the entire lower extremity. Again, caution should be placed on exercises that produce shear forces in patients with patellofemoral lesions.

The remodeling phase occurs from 12 through 32 weeks postoperatively. During this phase, there is a continuous production of matrix, with further remodeling into a more organized structural tissue. The tissue at this point has the consistency of soft plastic upon probing.[20,43] As the tissue becomes more firm and integrated, it allows for more functional training activities to be performed, as well as elliptical, bicycle, and a gradual walking program.

The final maturation phase can last up to 15 to 18 months, depending upon the size and location of the lesion. By the end of this phase, the stiffness of the cartilage resembles that of the surrounding tissue.[20,43] The duration of this phase varies based on the several factors such as lesion size and location. Basic science studies have shown that it may take up to 6 months for the graft site to become firm, and at least 9 months to become as durable as the surrounding

healthy articular cartilage.[20,43] Thus, low-impact activities are initiated by months 5 to 6 and progressed to moderate-impact activities from months 7 to 9 as tolerated.

CONCLUSION

The rehabilitation process following articular cartilage repair procedures is vital to the long-term success and functional outcome of these patients. The rehabilitation programs discussed are based on our current understanding of articular cartilage and the natural healing response observed following articular cartilage repair procedures. Rehabilitation is based on several key principles used to facilitate the repair process by creating a healing environment, while avoiding deleterious forces that may overload the healing tissue. It must also consider any concomitant surgery performed. The basic principles outlined in this paper may be applied and integrated as our understanding and clinical use of the next generation of procedures, such as collagen-covered ACI and matrix-induced ACI, evolve.

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