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Biomechanical Outcomes of Cartilage Repair of the Knee

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Abstract

Cartilage repair and restoration has become an increasingly popular surgical technique to provide symptomatic relief to young patients with focal articular cartilage defects. Given the high level of interest and improvement in surgical techniques to perform cartilage repair or restoration, it is important that patient-reported, surgical and functional outcomes are evaluated both in the short term and long term. Despite the high levels of interest in cartilage repair and restoration techniques, there are few studies that have evaluated the effects of cartilage surgery on biomechanical and neuromuscular function of the joint and the lower extremity. The focus of the following review is to evaluate the current evidence available on biomechanical functional outcomes after cartilage repair with clinical applications to the rehabilitation process.

Keywords

cartilage repair; cartilage restoration; surgical techniques; knee biomechanics; rehabilitation

Articular cartilage defects of the knee have been documented in over 60% of all patients undergoing knee arthroscopy.¹ In the athletic population, the prevalence of these lesions may be even greater than in the general population.² Patients with focal cartilage defects may have major problems with pain and loss of function, equivalent to those scheduled to undergo total knee arthroplasty.³ Cartilage repair or restoration is a reliable option for symptomatic patients who have failed nonoperative treatment. Clinical outcomes measures are important to aid in the development and optimization of articular cartilage treatment strategies. As techniques in cartilage surgery continue to improve, it is vital that high level evidence be employed to evaluate patient-reported, surgical and functional outcomes. Despite the high levels of interest in cartilage repair and restoration techniques, there are few studies that have evaluated the effects of cartilage surgery on biomechanical and

neuromuscular function of the joint and the lower extremity. The focus of the following review is to evaluate the current evidence available on biomechanical functional outcomes after cartilage repair with clinical applications to the rehabilitation process.

As one of the primary load-bearing surfaces of the body, the knee joint surface endures high loads not only during high impact sports activities but also during activities of daily living. The knee joint may be subjected to loads two to eight times body weight during simple squatting tasks and gait.⁴⁻⁷ The articular surface of the knee is able to withstand these high loads due to its highly durable, biologically active tissue, with nearly frictionless and elastic material properties that withstand large compressive loads without permanent deformation. The biphasic nature of articular cartilage, comprised primarily of water and extracellular matrix, provides unique properties necessary to sustain a healthy knee joint, despite the heavy load demands sustained by the tibiofemoral and patellofemoral surfaces. However, the hypocellular, relatively avascular environment of articular cartilage hinders the healing potential of damaged articular cartilage. In the setting of an neural structure, patients may have large cartilage defects with minimal symptoms and subconscious gait alterations that may help unload damaged areas. Given the poor healing potential of articular cartilage lesions and the subsequent disability, there is a high interest in cartilage repair and tissue engineering techniques.

The knee joint is subjected to a variety of external loads (ground reaction forces and perturbations) and internal loads (muscle forces, joint reaction forces as a result of the anatomy) during functional activities such as gait, squatting, and activities of daily living. Muscles that span the knee joint as well as muscles that do not cross the joint can lead to high knee joint loads. Small alterations in walking kinematics, in particular knee flexion angles may significantly affect the magnitude of knee joint forces.⁸⁻¹⁰ Alterations in chondral surfaces and gross cartilage defects alter the load-bearing capabilities of the surrounding tissue.^{11,12} The rims of chondral defects bear significantly higher loads than healthy cartilage areas and may lead to defect progression.¹²⁻¹⁷

Knee joint loading profiles in both the tibiofemoral and patellofemoral compartments are influenced by the thickness of the articular cartilage, the joint's radii of curvature, the shape of the menisci, mechanical axis, patellofemoral alignment, and ligamentous stability. In the setting of cartilage repair, achievement of joint surface congruity and defect filling likely decreases the rim stresses of articular cartilage at focal defect areas (Fig. 1). Theoretically a decrease in rim stresses may prevent or minimize defect progression and may even lead to full integration of cartilage to surrounding normal articular cartilage and underlying subchondral bone. Cartilage repair techniques such as abrasion arthroplasty, drilling, and microfracture penetrate the subchondral bone to induce fibrocartilage formation and demonstrate positive functional and objective outcomes in the short term. However, longer follow-up studies indicate that functional and objective outcomes after these marrow stimulation techniques decline with time, particularly for larger defects.¹⁸⁻²⁶ In contrast, cartilage restoration techniques (osteochondral autograft, osteochondral allo-graft, mosaicplasty and autologous chondrocyte implantation [ACI]) that incorporate more hyaline-like cartilage in focal defects may offer more long-term successful outcomes.²⁷

Knee Joint Biomechanics

Two separate layers of calcified and uncalcified cartilage contribute to the biomechanical properties of articular cartilage in the knee. The uncalcified region (includes superficial, transitional and deep zones) possesses a unique structural composition and provides both tensile strength and resilience to compression and deformation. The calcified layer is deep to the tidemark, overlies the highly vascularized subchondral bone region, and provides an attachment to the underlying subchondral bone.

Tibiofemoral Joint

Knee joint motions between the femoral condyles and the tibial plateau can occur in all three planes (sagittal, frontal, and transverse) with six degrees of freedom that allow 12 directional motions (Fig. 2).^{28,29} The tibiofemoral joint can rotate in the sagittal plane by flexion and extension, in the frontal plane by abduction and adduction and in the transverse plane by internal and external rotation. Translations of the tibiofemoral joint occur in the sagittal plane anteriorly and posteriorly, in the frontal plane medially and laterally, and in the transverse plane by compression and distraction (Fig. 2). While the knee can move in all 12 of these potential directions, with the exception of sagittal plane rotations (flexion/extension), most of these motions occur through a relatively limited range. In addition, motions in the transverse and frontal planes (as well as sagittal plane translations) are influenced by the amount of knee flexion and the anatomy of the femur, tibia, and surrounding ligamentous structures.

Movements between the articulating surfaces of the tibia and femur play key roles in knee joint function. The menisci also contact both the tibial and femoral surfaces. The menisci decrease the stress transmission to the articular cartilage by increasing the surface contact area.³⁰ The contact points of the tibia and femur in the sagittal plane move posteriorly during knee flexion via a combination of both rolling and gliding motions. The femoral condyles glide anteriorly as the femur rolls posteriorly during flexion, reducing the posterior progression of the rolling effect and preventing the subluxation of the femur off the back of the tibia.^{30,31} There is a significant asymmetry in the anatomy and kinematics of the medial and lateral tibiofemoral compartments.^{32,33} The medial compartment, with the medial tibia possessing a firmly attached medial meniscus on two angled flat surfaces of the medial tibia and articulating with the convex medial femoral condyle, experiences minimal gliding in the anterior-posterior directions and minimal rotations in the transverse plane in unconstrained, nonweight-bearing conditions.³⁴ In contrast, the lateral compartment is composed of a convex on convex articulation, due to the shape of the lateral tibial plateau.^{35,36} Increased anterior-posterior glide, as well as transverse rotations during unconstrained, nonweight-bearing conditions occur in the lateral compartment due to the less adherent lateral meniscus and less bony constraint imposed by the lateral plateau relative to the medial plateau.³⁷ Thus, the center of rotation of the knee joint during nonweight-bearing conditions is likely in the medial compartment.^{32,37,38} In contrast to nonweight-bearing conditions, knee kinematics are different during gait. Koo and Andriacchi demonstrated that during gait, the center of rotation of the knee joint is primarily on the lateral side with the medial side demonstrating greater anterior-posterior translation.³⁹ The convex-concave surface contact

area of the medial compartment is much greater than the convex-convex surface contact area of the lateral side during weight-bearing. The greater potential surface area that may change with an alteration in gait (i.e., that may occur with pathology such as osteoarthritis) may make the medial compartment more sensitive to small changes in knee joint kinematics.³⁵

The Patellofemoral Joint

The bony anatomy of the patella and the trochlea of the femur provide inherent stability to the patellofemoral joint, with the medial and lateral facets of the posterior surface of the patella articulating and tracking within the trochlear groove. The superior 75% of the posterior surface of the patella is made up of articular cartilage and with thicknesses up to 5 to 6 mm, it has the thickest articular cartilage surface in the human body.³⁴ Since contact pressures of up to 12 MPa may occur during maximal extensor mechanism contractions, the thick articular surface and smooth congruent surface contact between the trochlea and patella are necessary for optimal performance of the extensor mechanism.^{40–42}

The patella undergoes both a rolling and gliding motion along the articulating surface of the femur as it increases the mechanical advantage of the extensor muscles. The quadriceps muscles (rectus femoris, vastus lateralis, medialis, and intermedius) which are important for knee extension movements, originate from the pelvis (ilium) and proximal femur. The quadriceps muscles wrap around the patella and unite to form the patellar tendon that attaches the patella to the tibial tubercle. The patella serves as a fulcrum for quadriceps muscle moment generation since it displaces the quadriceps tendon anteriorly and increases the internal moment arm of the knee extensor mechanism (the larger the internal moment arm, the greater the internal moment produced per level of force generation).⁴³ The knee flexion angle influences the patella-trochlea surface area contact and pressure. The patella engages with the trochlea between 20 and 30 degrees of knee flexion. Near full extension of the knee, the inferior surface of the patella articulates with the superior portion of the trochlea in a single contact, horizontal fashion. As knee flexion increases, more proximal portions of the patella contact the trochlea and the horizontal contact transitions into separate areas of contact on the lateral and medial facets at ~130 degrees of knee flexion.⁴² Patellofemoral surface contact increases ~24% during flexion with weight-bearing activities compared with nonweight-bearing conditions.⁴⁴ The highest contact pressures in the patellofemoral joint occur between 60 and 90 degrees of knee flexion.⁴⁰

Biomechanics of Cartilage Rehabilitation

The rehabilitation program after cartilage repair is critical to optimize surgical outcomes. Physiologic healing and chondrocyte protection are paramount to the success of the surgical procedure. However, this healing and protection must be balanced with optimization of the rehabilitation program. The goals of the rehabilitation process should be to minimize disability, immobilization, and overall morbidity accounting for the complications that may occur with small arthroscopic procedures, and/or large open procedures combined with osteotomies.

Due to the high variability in lesion location, nature of the defect and surgical procedures performed, personalized rehabilitation strategies are necessary. Awareness of the location of

the defect, size of the defect, concomitant procedures, type of healing response anticipated for the surgical procedure performed and the goals of the patient for return to both activities of daily living and high level activities such as sports are important considerations during the rehabilitation stage.⁴⁵ Currently, there is a minimal evidence in the literature regarding rehabilitation programs following cartilage repair. Most of the available literature about rehabilitation is based on biomechanical theories and expert or nonexpert opinion.

Although protection of the knee joint after a surgical intervention is important, joint immobilization has known detrimental effects on muscle and articular cartilage.⁴⁶ Even short-term immobilization can induce articular cartilage atrophy and although reversible, full restoration of cartilage integrity may not occur.^{47–49} Animal studies demonstrate that cartilage repair techniques supplemented with early mobilization show superior tissue regeneration and integration.^{50–52} Successful cartilage repair is predicated on chondrocyte viability, integration of the new repair tissue with the surrounding healthy tissue, and the ability of the repair to withstand high mechanical stresses. In the early postoperative period after cartilage repair, continuous passive motion (CPM) is often used within the first few hours after surgery to counter the immobilization effects, to enhance metabolic and nutritional activity of the cartilage, and to prevent joint stiffness.^{52,53} However, CPM recommendations are largely based on basic science and animal model studies with few in vivo clinical studies available to support this accepted clinical practice.⁵⁴ A recent systematic review revealed only four human, in vivo studies that evaluated the use of CPM after cartilage repair.^{53,55–58} No randomized, controlled studies were available to support the use of CPM and all studies varied significantly in the recommendation of time and duration of use (from 6 to 8 hours per day for 6 days up to 8 weeks of use).^{53,55–58} Rodrigo et al showed improvement of the defects on second look arthroscopy in patients that used a CPM compared with the control group; however, no correlation to functional outcome was reported.⁵⁸ Although only available on a small group of subjects, histological outcomes on second look arthroscopy do not show significant differences between patients that use CPM and those that only perform active range of motion.^{57,58} In general, rehabilitation programs encourage early, interval increases in joint motion starting with passive range of motion activities. Active joint range of motion may have higher joint-contact pressures than passive range of motion; thus most programs begin with passive range of motion with slow progression into active range of motion and strengthening activities.⁵⁹

Weight-bearing guidelines after cartilage repair vary widely in the literature.⁵⁹ In general, most recommendations use separate guidelines for femoral/tibial defects compared with patellofemoral defects. The mechanics of weight-bearing and walking may increase the risk of articular cartilage breakdown when the normal mechanical environment and balance between loading and biological maintenance of cartilage is compromised.^{60,61} During the early postoperative weeks following cartilage repair, the cells contained in the defect start differentiating and develop into a soft repair tissue that is highly vulnerable to, but also may be stimulated by, mechanical loads.⁶² It may take up to 2 years for the repaired lesion to develop into the optimal cartilage phenotype.^{63,64} Small mechanical loads may promote cartilage metabolic activity and nutrition, similar to CPM effects. Thus, the challenge in the early postoperative period is to provide small bouts of loading stimulus to the healing articular lesion, without subjecting the cartilage repair site to significant, potentially

damaging mechanical overload.⁶⁵ The restriction of weight-bearing in the early postoperative phase, particularly in the tibiofemoral joint may theoretically protect the cartilage repair and decrease the mechanical stress that the repair site is subjected to during the most vulnerable time period.

Often patients with cartilage repair in the tibiofemoral compartment are restricted to nonweight-bearing in the first few weeks after restoration, with slow progression over 2 to 12 weeks to full weight-bearing conditions.⁴⁵ Weight-bearing movements result in increased pressure on the tibiofemoral articulation throughout the entire arc of knee motion and contact forces can reach four times body weight at 90 degrees of knee flexion.^{66,67} In addition to restriction of the amount of weight exerted on the limb after cartilage repair, clinicians should consider other external loads during gait that may subject the knee to mechanical stresses. Ebert et al found that in ACI patients, the contribution of ground reaction force at different percentages of weight-bearing status demonstrate a large variability in kinematic, spacio-temporal parameters, and external knee moments.⁶⁸ Thus, in addition to the ground reaction force, other variables may affect the external loads experienced by the knee joint during gait. Also, from a patient perspective, despite strict instruction and practice of partial weight-bearing restrictions on bathroom type weight scales it is difficult to accurately replicate “partial weight-bearing” restrictions.⁶⁹ To prevent mechanical shear and high contact pressures during the most vulnerable healing time after cartilage repair, weight-bearing restrictions have often been strict, with slow progressions. However, there is a limited good evidence regarding how weight-bearing restrictions affect functional outcomes.

An assessment of ACI biopsies taken on 11 patients (12 graft sites on femoral condyles) at second-look arthroscopy at 3 to 7 years after the initial procedure demonstrated stiffness measures of 90% or more of the value of controls in 8 of the 12 biopsies and good to excellent grading of integration of graft to the surrounding cartilage in 10 of the 11 subjects. All patients followed a weight-bearing protocol that started with gradual weight-bearing for 8 weeks with progression to full weight-bearing at 10 weeks.⁷⁰ A randomized control trial that evaluated clinical outcomes in “accelerated” versus “delayed” weight-bearing for matrix-associated ACI of the femoral condyle demonstrated no differences in clinical outcome 2 years postoperatively. The accelerated group was allowed 20% weight-bearing for the first 2 weeks, 50% weight-bearing between 2 and 4 weeks and progression to full weight-bearing after 6 weeks. The delayed group was allowed toe-touch weight-bearing only until 4 weeks postoperatively, followed by 20% weight-bearing 4 to 6 weeks, 50% weight-bearing at 6 to 8 weeks, with gradual increase to full weight-bearing at postoperative week 10.⁷¹ Ebert et al employed an accelerated rehabilitation that allowed full weight-bearing at 8 weeks compared with a delayed full weight-bearing until 11 weeks postoperatively after matrix-induced autologous chondrocyte implantation (MACI) in the femoral condyle resulted in the accelerated group demonstrating improved function, reduced knee pain, and no significant changes on MRI at 3 months postoperatively compared with the delayed group.⁷² Thus, early pilot studies demonstrate that it may be possible to accelerate weight-bearing loads in femoral articular cartilage repair without compromising the repair.

In contrast to tibiofemoral cartilage repair rehabilitation, most patellofemoral cartilage repair protocols allow for immediate weight-bearing with the knee in full extension or with restricted range of motion to 0 to 30 degrees of knee flexion. This is theoretically a “safe” range of motion for patellofemoral patients because the patella does not engage with the trochlea until ~20 degrees of knee flexion and the patellofemoral joint reaction force is 50% of the quadriceps force in full knee extension.^{40,73} In contrast to tibiofemoral cartilage repair, patients with patellofemoral pain or patellofemoral cartilage restoration likely benefit from weight-bearing restrictions and exercises that minimize the patellofemoral joint reaction forces but maximize quadriceps forces. van Eijden et al demonstrated that between 70 and 100 degrees of knee flexion, the patellofemoral joint reaction force is equal to the quadriceps force.⁷³ In contrast, from full knee extension to 40 degrees of knee flexion the patellofemoral joint reaction force is 50 to 90%, respectively.⁷³ During squatting activities, the highest patellofemoral joint forces and stresses occur at ~90 degrees of knee flexion. Increased external loads (increased weight) significantly increases the patellofemoral joint stresses.⁷⁴ Targeted rehabilitation exercises that avoid larger knee flexion angles may allow for quadriceps strengthening exercises that allow for lower patellofemoral joint stresses. However, timing of implementation of quadriceps activation and maximal muscle force recruitment may need to be modified and taken into consideration for cartilage procedures that are combined with tibial tubercle osteotomies.

Biomechanical Outcomes

Currently, there is a paucity of literature that evaluates functional outcomes after cartilage restoration procedures. The majority of outcome studies utilize patient-reported outcomes via surveys to “assess” function, return to activities of daily living, sport, and overall patient satisfaction. In 2009, Mithoefer et al identified 20 studies that described return to sports on 1363 patients after cartilage repair. Almost 75% of athletes were able to return to sports within seven and 18 months of cartilage repair. However, of the patients that returned to sports only 65% returned to the preinjury level of participation. The ability to return to preinjury level of sport after 3 to 5 years was significantly better after autologous chondrocyte procedures than for microfracture or osteochondral transfer patients.¹⁹ While return to sport indirectly evaluates overall functional outcome after cartilage procedures, the specific functional outcomes such as strength and neuromuscular performance after cartilage repair is not well known.

A rigorous systematic review of the literature on March 1, 2012 identified only two peer-reviewed studies that evaluated the functional outcome of gait after cartilage restoration,^{72,75} four peer-reviewed articles that evaluated strength measures,^{76–79} and two studies that evaluated overall function with a collective functional index score (hop tests and strength measures).^{78,79} All gait studies were performed in patients that had undergone MACI. Functional measures of gait have not been directly measured after cartilage repair for any other cartilage repair techniques. Ebert et al conducted a randomized controlled trial (RCT) that investigated gait differences between MACI patients (medial or lateral femoral condyle lesions) that underwent an accelerated weight-bearing protocol (full weight-bearing by 8 weeks) versus a traditional weight-bearing protocol (full weight-bearing by 11 weeks) after surgery with gait analyses at 3, 6, and 12 months postsurgery.^{72,75} Both groups had similar

ground reaction forces and spatio-temporal gait parameters during gait postoperatively. However, compared with healthy controls, both the accelerated rehabilitation group and the traditional rehabilitation group had significantly reduced knee extension moments, which persisted 12 months post-surgery. The traditional group also demonstrated significantly reduced peak knee adduction and flexion moment compared with healthy controls that was not found in the accelerated rehabilitation group.^{72,75}

Muscle atrophy and weakness is a common clinical manifestation after knee surgery.^{77,80-82} Quadriceps muscles weakness alters the mechanical loading of the articular cartilage and is necessary for resisting external ground reaction forces and external perturbations.⁸³ Poor knee joint control and abnormal joint loading may play a role in the development of osteoarthritis.⁶⁰ Studies by Ebert et al, Løken et al, Kreuz et al, and Van Assche et al indicate that significant strength deficits may occur after cartilage repair and may persist even 4 to 5 years postoperatively.⁷⁶⁻⁷⁸ Ebert et al found a significantly reduced knee extensor torques in the operative limb compared with the contralateral limb five years following MACI at all isokinetic speeds tested.⁷⁶ Kreuz et al demonstrated that isokinetic strength in patients 4 years after cartilage repair with scaffold-assisted ACI was significantly lower in the operative limb compared with the healthy control limb, with extension peak torque deficits greater than flexor peak torque deficits.⁸⁴ Loken et al demonstrated that compared with the contralateral limb, patients had a 10 to 20% extensor strength deficit in the leg that had cartilage repair from 2 to 7.4 years after the surgery.⁷⁷ Van Assche et al evaluated knee extension deficits in ACI patients compared with microfracture patients presurgery and at 6 months and 2-year follow-up after surgery.⁷⁸ Both the microfracture and ACI groups experienced a decrease in strength after surgery at the 6-month time point. After 2 years of cartilage repair, 26% of the patients had significant extension strength deficits. Adequate muscle control after cartilage repair is critical to function during activities of daily living. Despite supervised rehabilitation many patients exhibit significant strength deficits that persist for years after cartilage repair.

Lower extremity asymmetry in strength and functional abilities has been linked to increased risk for lower-extremity injury. Persistence of lower-extremity functional asymmetries may pose a significant risk to injury in both the rehabilitated and healthy contralateral limb.⁸⁵⁻⁸⁸ With a large number of cartilage repair patients returning to moderate-to high-level activities, evaluation of neuromuscular strength and control symmetries is important to minimize the risk for injury upon return to sport. However, there is minimal evidence in the literature about the effects of cartilage repair on lower extremity functional asymmetries. There is an evidence of significant strength asymmetries in limbs after cartilage repair, particularly for quadriceps function and these may persist up to 5 years after cartilage repair.^{76-78,84} Van Assche et al found that at 2 years after ACI or micro-fracture, 30% of the patients had asymmetries greater than 85% compared with their contralateral limb for strength and functional hop tests.^{78,79} At 2 years postoperatively, micro-fracture patients and ACI patients had similar functional outcomes.⁷⁹ Persistent abnormal neuromuscular and bio-mechanical risk factors, such as lower limb motion and loading asymmetries, may increase risk for future injury and indicate that cartilage repair patients may require more targeted interventions before return to moderate- to high-level sports activities.

Concomitant Procedures: Osteotomy Effects on Biomechanics

Osteotomies have been utilized independently as well as in combination with cartilage repair techniques to improve symptoms of cartilage pathology and patellofemoral symptoms. In the tibiofemoral joint, both opening- and closing-wedge, valgus-producing, high (proximal) tibial osteotomies have gained wide acceptance as a technique to off-load damaged cartilage areas in an attempt to provide symptom relief and prolong time to total knee arthroplasty.⁸⁹ For patients with unicompartamental knee pathology, this technique redistributes the loads within the tibiofemoral joint. In the setting of cartilage repair, a concomitant osteotomy can be used to off-load the repair site and perhaps help with the healing process.^{89,90} In general, most surgeons aim for over-correction of the varus malaligned medial compartment osteoarthritic patient versus neutral correction in the cartilage repair or restoration patient. In the patellofemoral joint, it is common to find patients with significant patellar maltracking, instability and/or malalignment, which are often addressed at the time of cartilage repair. Tibial tubercle anteriorization (Fig. 3) or anteromedialization can significantly reduce patellofemoral contact stresses.⁹¹⁻⁹³ Maquet demonstrated that elevation of the tibial tubercle by 2 centimeters reduces patellofemoral joint reaction forces by up to 50% at 45 degrees of knee flexion.⁹⁴ There is increased evidence that patellofemoral cartilage repair, in particular ACI techniques, have improved outcomes for patients who have concomitant tibial tubercle osteotomies with either anteromedialization or anteriorization than ACI alone.⁹⁵⁻⁹⁷ Bauer et al demonstrated significant improvements in patient-reported outcomes after MACI combined with high tibial osteotomy; however, MRI results demonstrated poor filling of cartilage defects postoperatively.⁹⁰ Gigante et al also demonstrated significant improvement in patient-reported outcomes after combined tibial tubercle osteotomy and ACI in the patellofemoral joint 36 months after surgery.⁹⁸ Unfortunately, no current studies are available that report measured neuromuscular performance outcomes in patients with concomitant cartilage repair and osteotomy procedures. Overall, patients with significant anatomic malalignment may benefit from concomitant procedures that address both the alignment and cartilage pathology, but there is a significant need for research in this area.^{90,99}

Limitations in Current Literature Regarding Biomechanics after Cartilage Repair

Cartilage repair and restoration techniques are increasingly recognized as surgical interventions that may significantly alter patient symptoms and perhaps even modify disease progression of articular cartilage pathology. However, as the field of cartilage repair has grown, there has been a gap in the literature for evidence on functional outcomes. Even more challenging is the heterogeneity of patients, location of lesions, size of lesions, concomitant injuries, and types of procedures that often become grouped into mean, pooled data to meet statistical power.¹⁰⁰ This poses a significant challenge to clinicians for evaluation of outcomes after cartilage repair. In addition, very few studies exist evaluating functional, biomechanical outcomes of cartilage repair, and the current literature base is limited to short- to moderate follow-up studies. Long-term studies, in terms of functional outcome, are currently unavailable.

Conclusion

Clinical outcomes measures are critical to the development and optimization of evidence-based treatment strategies. With the advancements in cartilage restoration, it is imperative that patient-reported surgical and functional outcomes be evaluated with high level, thorough, systematic research methods. Despite the high level of interest in cartilage restoration techniques and outcomes, there are few studies that evaluate the effects of cartilage restoration on biomechanical and neuromuscular function. The limited studies available indicate that significant strength deficits and gait alterations may occur after cartilage restoration procedures and persist up to 5 years or more postoperatively. Future work should focus on determining functional outcomes such as strength, neuromuscular function and return to activities of daily living and sport. In addition, development of clinical assessment tools that help evaluate and improve functional deficits during the rehabilitation phases of cartilage restoration may aid in the assessment of outcomes as well as improve rehabilitation strategies.

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Figure 1.

Images of a trochlea articular cartilage defect demonstrating reconstitution/filling of defect and integration of implant after autologous chondrocyte implantation (ACI). (A) Picture of trochlea before ACI treatment demonstrating large cartilage defect, (B) picture of trochlea during open ACI procedure, and (C) picture of the same trochlea at second look arthroscopy 8 months after ACI.

Figure 2. Rotations and translations of the tibiofemoral joint. Reproduced from Quatman CE, Quatman CC, Hewett TE. A “Plane” Explanation of Anterior Cruciate Ligament Injuries. *Sports Med.* 40 (9); 729–746, with permission from Adis, a Wolters Kluwer business (© Adis Data Information BV 2010. All rights reserved).

Figure 3.
Tibial tubercle osteotomy with anteriorization to reduce patellofemoral contact stresses.